An Investigation Report On The Necessity And Feasibility For Development Of A Structural Damage Diagnostic And Monitoring System For Rocket Engines

-- A Final Report For The Grant NAG3-2055

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Table of Contents

Appendix I - A Technical Paper

Shen, J.Y., Sharpe, L., Jr. and Jankovsky, A.L., "**An Overview of Vibrational-Based Nondestructive Evaluation Techniques**", Prceedings of the International Symposium on Non-Destructive Damage Evaluation (NDE) of Aging Infrastructure and Aging Aircraft, Airport, and Aerospace Hardware, San Antonio, Texas, March 31 - April 2, 1988, pp.117-128.

Appendix II - A Technical Paper

Shen, J.Y. and Sharpe, L., Jr., "**Non-Destructive Damage Identification of Flexible Aerospace Manipulating Systems**", Proceedings of the SPACE'98 Conference, Albuquerque, New Mexico, April 26-30, 1998, pp.86-93.

Appendix III - A Proposal for Fiscal Year 1998-1999

Shen, J.Y. and Sharpe, L., Jr., "**Development of a Structural Damage Diagnostic and Monitoring System for Rocket Engines, Phase I: Structural Modeling for Typical Engine Components**", Submitted to NASA Lewis Research Center, December 1997.

1. Summary

The research project, entitled **"Feasibility Investigation on the Development of a Structural Damage Diagnostic and Monitoring System for Rocket Engines"**, is funded by NASA Lewis Research Center during the period from July 1st, 1997 to June 30th, 1998 with amount of $25,000 (Grant No. NAG3-2055). The research activity for this project is mainly to investigate the necessity and feasibility to develop a structural health monitoring system for rocket engines, and to carry out a research plan for further development of the system. A presentation was given by Dr. Shen, the principal investigator, at NASA Lewis Research Center on July 28th, 1997. More than one hundred technical papers have been searched and reviewed during the period. A technical paper entitled **"An Overview of Vibrational-Based Nondestructive Evaluation Techniques"** has been presented at the International Symposium on Non-Destructive Damage Evaluation (NDE) of Aging Infrastructure and Aging Aircraft, Airport, and Aerospace Hardware held at San Antonio, Texas, March 31 - April 2, 1998 (*Appendix I*). Preparation for future research has been started, for example, searching for applicable damage detection criteria and verifying the criterion by computer simulation. As a result, another paper entitled **"Non-Destructive Damage Identification of Flexible Aerospace Manipulating Systems"** has been presented at the SPACE'98 Conference held at Albuquerque, New Mexico, April 26-30, 1998 (*Appendix II*). Four undergraduate students were involved in the literature searching and technical training process. They were Mr. Raheen Beyah and Ms. Donna Sexton (Electrical Engineering majors), Mr. Marques McCammon and Ms. Nicole Calloway (Mechanical Engineering majors). Total spending for student salary was $3468. The future research plan has been carried out. As the first step of the overall research plan, a proposal for the next fiscal year has been submitted to NASA Lewis Research Center (*Appendix III*).

2. Proposed Tasks

The idea was conceived from NASA's effort in developing a generic post-test/post-flight diagnostic system for rocket engines. The ability to automate the functions performed by the engineers would benefit both current and future rocket engines. NASA's generic automated diagnostic system consists of three major sections under the Session/Message Manager: the Intelligent Knowledge Server (IKS) Section, the Support Application Section, and the Component Analysis Section, as shown in the Figure 1 of the system's architecture.

(1) Intelligent Knowledge Server Section: which provides a function that is basic to the data handling of the diagnostic system. It handles large amounts of data and performs the "intelligent" access to the required information sources. The tasks involved include: maintenance of local database information, providing muli-database management, providing high-level math and property queries, performing data retrieval, presenting data in a standard format, performing sensor or data validation and reconstruction, highlighting numerical points of interest, providing user or system customized tables, and providing knowledge about the previous tests with a similar anomaly.

(2) Support Application Section: which provides computer tools to the assessment of the engine system. The major tools in assessing and automating the data review process are CAE tool and Feature Extraction tool. The CAE tool provides capabilities, such as, plotting, statistical analysis, and signal processing. The Feature Extraction tool is used to extract characteristic and
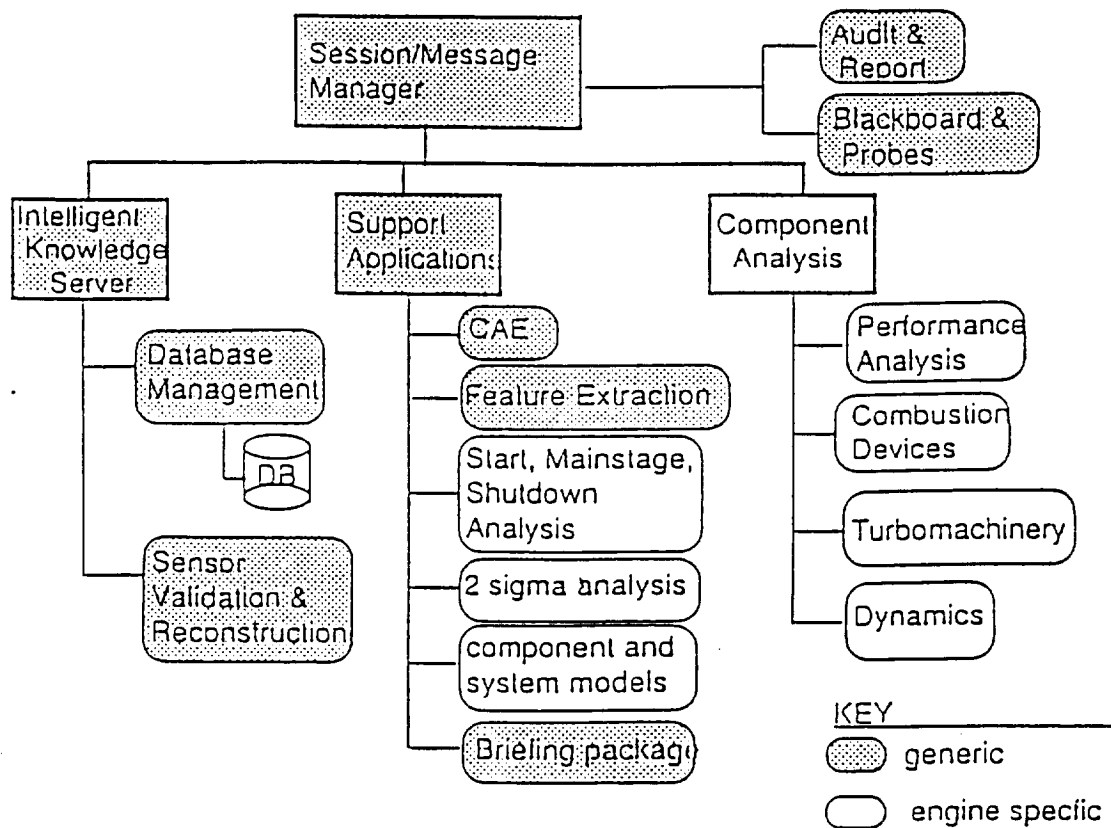
Figure 1 Architecture For Post-Test/Post-Flight Diagnostic System

trend information, and produce a feature table which will help the engineer to interpret the data. Other application modules that are included in the system are the startup analysis, mainstage analysis, shutdown analysis, two sigma exception analysis, SSME component and system models, and briefing preparation module. The startup, mainstage, shutdown, and two sigma exception analyses are application modules required by the component analysis modules. They provide core analysis routines that implement standard analysis procedures used during a particular engine phase, and provide a map of the engine during normal operation. The component and system models are existing models currently used during the data review process. The briefing preparation module is capable of preparing the text, plots and graphs necessary for the data review presentations.

(3) Component Analysis Section: which contains four major engine-specific technical modules used to analyze the SSME propulsion system. These include the performance analysis module, the combustion devices module, the turbomachinery module, and the dynamic data module. The primary function is to review the data characteristics, and assess the condition of an engine component, or entire engine system.

Thus far, the automated diagnostic system has not functioned for detection of potential damages in the rocket engine structures. In reality, however, adding a module in the automated diagnostic system to monitor the healthy condition of rocket engine structures is a crucial task. The rigorous structural design specification, non-analytical predictable structural anomaly, and

hazardous working conditions make it necessary for frequent inspections of the structural components after an engine has been flown or tested. Toward this end, a new module, which functions as a non-destructive structural damage diagnosing and monitoring sub-system, has been suggested to be added and consistent with the existing NASA's automated diagnostic system. The function of this sub-system is to detect damage as it is incurred by the engine structures, determine the location and extent of the damage, predict whether and when catastrophic failure of the structure will occur, and alert the operators as to how the performance of the structure is affected so that appropriate steps can be made to remedy the situation. This module should be consistent with the existing NASA's automated diagnostic system so that the generic core of the existing system's software can be used in common, that is, the general data review functions and software system handlers will be provided by the original system, and any customized software for a particular engine within the original software can also be shared with the new module. Many automated features, such as, a plotting package, statistical routines, and frequently used engine and component models, provided by the existing system can also be referred. The same guidelines used in that system will be followed in the development of the structural module so that the two requirements for the existing system will also be satisfied for the new module. This new module consists of five sub-modules: Structural Modeling, Measurement Data Pre-Processor, Structural System Identification, Damage Detection Criterion, and Computer Visualization, as shown in the Figure 2.
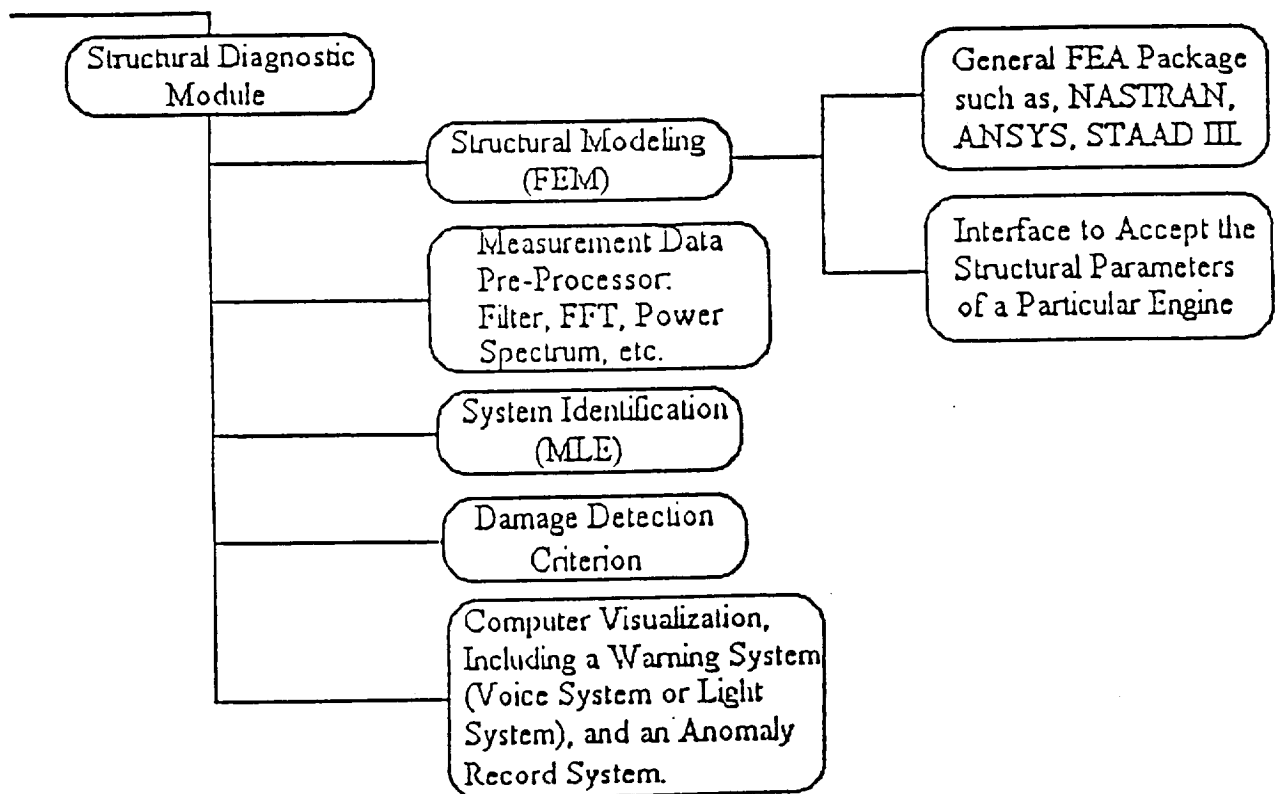

Figure 2 Components of the Proposed New Module

The structural modeling module will contain two sessions: a general finite element analysis package, such as, NASTRAN, ANSYS, STAAD III, etc., and an interface to accept the structural parameters of a particular engine which is thus engine-specific. The data pre-processor module will basically complete the tasks, such as, filtering, Fast Fourier Transformation (FFT), power spectrum analysis, etc. The system identification module is programmed to extract modal properties from the experimental data. Based on those modal properties, the damage detection module then localizes the damage sites. The purpose of computer visualization module is not only for providing visual impression, but also for instantly warning and anomaly recording. For some extreme cases, the incipient-type damage would progressively expand so fast that there might not be enough time to avoid a catastrophic failure, the recorded message of structural failure stored in "*black box*" would definitely have unique value for cause analysis. If this type of system had been installed, then, the chaotic situation after the crash of TWA Flight 800 would never have occured.

In order to complete the entire system, the research activities will include theoretical derivation, computer software development and visualization, instrumentation setup, and experimental study. The theoretical derivation covers three core parts: structural modeling, structural system identification, and damage criterion establishment. The structural model begins with conventional finite element model, and is then transferred into state-space form if it is necessary which might provide some potential features for control purpose. The structural system identification algorithm is an advanced time-domain technique based on maximum likelihood estimation theory, or some other advanced techniques such as Eigensystem Realization Algorithm. The damage detection criterion will be chosen from one of the advanced vibrational-based assessment techniques. The possible candidate may be the residual modal force method combined with modal sensitivity method, or damage index method. In order to develop a system for real-world engineering application, the research activities will also include computer software development and visualization, instrumentation setup, experimental measurements, and data acquisition and processing. The state-of-the-art theories and practices are systematically merged and integrated in the development of the system, and the system will be verified through the real world application of existing rocket engines.

3. Necessity to Add a New Module for Monitoring Structural Healthy Condition

Adding a new module in the existing automated diagnostic system to monitor the healthy condition of rocket engine structures is a crucial task.

The complexity in structures, geometry, and material composition makes it impossible to predict structural anomaly analytically. Rocket engine is a very complex assembly consisting of a propellant/oxidizer supply and feed system, thrust chamber (a combination of a combustion chamber and an exhaust nozzle), and a cooling system. Liquid propellant stored in suitable tanks must be carried to the combustion chamber and injected into it at relatively high pressure. There are two common feed systems in use. They are the gas-pressurized feed system and the turbopump propellant feed system. For the turbopump propellant feed system, the pump is driven by a turbine, through a gear train, which in turn is driven by high-pressure gases from a gas generator. The combustion chamber must have an appropriate array of propellant injectors, and a volume in which the propellant constituents can vaporize, mix and

4

burn; attaining near equilibrium composition before entering the nozzle. For a solid-propellant rocket, the combustion chamber is a high-pressure tank containing the solid propellant and sufficient void space to permit stable combustion. An ignition system is required for both liquid and solid propellant rockets. In an attempt to offset the thrust loss associated with over expansion, nozzle shapes other than conventional internal-flow configuration have been developed. The plug nozzle and the expansion-deflection nozzle are two examples. A suitable cooling system is required. Three basic cooling methods are commonly used. For liquid propellants, a regenerative cooling system is popular, which uses the fuel or oxidizer as a coolant flowing in tubes such as nickel tubes, or passing directly outside the chamber wall. Heat loss from the hot propellant is added to the incoming propellant. For a solid propellant, it is common to surround the nozzle walls with a mass of metal or other material which absorbs heat from the hot surface. Additional cooling may be attained by the vaporization or sublimation of material from the inner surface of the chamber wall or from the wall itself. The injection of liquids or gases through porous walls is called sweat cooling, and the intentional loss of wall material is called ablation cooling.

The geometry and material composition of each component are very complex as well. For example, many nozzles are composite structures. Near the nozzle throat, where heat transfer is most severe, the wall curvature and axial variations may significantly alter the wall temperature distribution. The wall heating rate varies considerably throughout a given nozzle, reaching a maximum near the throat. In many cases, the wall consists of a composite structure of varying thermal diffusivities, and in some cases the materials are highly anisotropic. The best material is used only in the throat region, while other materials, which may be lighter, cheaper, or easier to form, are sufficient in other regions. Consideration of such factors leads to mathematically complex analysis. In addition, certain non-analytic phenomena, such as surface erosion or chemical reaction, may be of great importance.

The rigorous structural design specification makes it possible to overstress the rocket engine structures. The performance of the rocket vehicle depends heavily on the mass of the engine. The total mass of the rocket vehicle consists of the mass of the payload, the propellant mass and the structural mass which includes the engine, guidance and control equipment, as well as tankage and supporting structures. Large payload ratio is desirable in general, especially for the research missions which require rocket transportation of instrument payloads. For a given mass of propellant carried and a given mass ratio, every decrease in the structural mass permits an increase of equal magnitude in the payload. Thus, it is advantageous to reduce the structural coefficient, that is, to design a very light tank and support structure. Reports showed that total structural mass is only 6% of the total initial mass in designing rockets. To achieve the desired light weight, design stresses are commonly much higher than those encountered in conventional earthbound structures. Stress levels in excess of 200,000 psi are common for high-strength steel-alloy structural components. Some of the lighter-alloy such as titanium-alloy structural components have withstood stress levels as high as 260,000 psi. This puts a very strict demand on the structural strength design of the vehicle.

There are a number of possibilities to overstress the rocket engine structures. The propellant mass is much larger than the payload. The mass of the propellant tanks and support structure may be larger than the payload. Much energy is consumed in the acceleration of the structure and tankage, less is available for acceleration of the payload. In order to reduce the energy consumed in simply lifting the propellant, it is desirable to reduce the burning time as much

as possible while accelerating the vehicle against a gravity field. However, very short burning time implies a very high acceleration, which may impose severe stresses on the structures.

Combustion pressure is another important factor influencing the overall vehicle performance. With the increase of the combustion pressure, the thrust chamber, hence rocket size, may be decreased for a given thrust. Offsetting this advantage is the increase of the thrust-chamber stresses. To alleviate the high-level stress, a relatively thick chamber wall may be used, but an increase in wall thickness will intensify the wall temperature problem. In addition, when the chamber pressure is lower than lower pressure limit or above the upper pressure limit, the combustion becomes erratic and unpredictable. The non-uniform burn-through may reduce the chamber pressure enough to extinguish the combustion before all of the propellants are consumed. Even if the combustion did not cease, the prematurely exposed chamber wall could fail due to overheating.

The hazardous working condition threatens the safety of the engine structures. Extremely high temperature brings difficulty in the design of rocket engine structures, and threatens the safety of the engine structures. For example, combustion temperatures of rocket propellants typically are higher than the melting points of common metals and alloys, and even of some refractory materials. Also, the strength of most materials declines rapidly at high temperature. For practical rockets, it is necessary to use high-temperature materials and/or special cooling effects, that is, greater solid conductivity and heat capacity. Using a certain type of cooling system such as regenerative cooling system is required. Even if a cooling system has been furnished, it is still necessary to make sure that the coolant temperature is below the local boiling temperature. Although local surface boiling might be permissible, overall boiling of the fluid is usually accompanied by rapid burnout of the chamber wall.

In summary, the rigorous structural design specification, non-analytical predictable structural anomaly, and hazardous working conditions are all factors that make it necessary for frequent inspections of the structural components after an engine has been flown or tested.

4. Tasks Completed During the Period

In an attempt to develop a structural health monitoring system for rocket engines, more than one hundred technical papers in the vibrational assessment area have been researched and briefly reviewed. A paper presented provides a comprehensive overview of various vibrational-based nondestructive evaluation techniques, including a brief introduction of the theoretical background of different methods, an analysis of their advantages and drawbacks, and a foresight of the applications of different methods towards different type of structures. The technique to identify damage in principle utilizes the changes in the vibration signature (natural frequencies and mode shapes) due to damage. As damage accumulates in a structure, the structural parameters (stiffness, damping, and mass) change. The changes in structural parameters, if properly identified and classified, can be used as quantitative measures that provide the means for assessing the state of damage of the structure. The problem is always formulated by giving the changes in the vibrational characteristics before and after the damage, then determine the location, magnitude and the type of damage.

A number of techniques for vibrational-based non-destructive damage assessment have been proposed in recent years, each with its own advantages and shortcomings due to particular assumptions, and many of them were basically evolved from modal updating procedures, not

particularly designed for structural damage detection. A major shortcoming of the approaches based upon modal updating procedure is that the comparison of the post-damage structural modes with those of pre-damage model often requires the solution of a nonlinear programming problem which is time consuming, and may generate ambiguous results. This may bring difficulty to damage detection applications. Selecting a method as the basis to establish a damage localization criterion must account for the complexity of modal analysis and testing methods and system identification techniques while still generating physically acceptable results. Some of the practical difficulties are such as dealing with nonlinear programming, random and systematic measurement errors, selecting optimal sensor configurations, and identifying relevant modes for damage detection. The efficiency of the method also highly relies on easiness of its numerical implementation. The paper would be considerably helpful for future research, and especially beneficial for the development of a structural monitoring system in choosing an applicable and realistic method as a basis.

Various vibrational-based assessment methods have been found and reviewed during this investigation period. One of the alternative approaches for structural health monitoring is to recognize the fact that modal vibration test data (structural natural frequencies and mode shapes) characterize the state of the structure. Assume that a refined finite element model (FEM) of the structure has been developed before damage has occurred. By refined, we mean that the measured and analytical modal properties are in agreement. Next, assume at some later time that some form of structural damage has occurred. If significant, the damage will result in a change in the structural modal parameters. The question is: Can the discrepancy between the original FEM modal properties and post-damage modal properties be used to locate and determine the extent of structural damage? The answer is *yes*. Damage generally causes changes in the mechanical properties of the structural system, such as stiffness. The problem of locating a damaged site on a structure can be equated to locating regions where the stiffness or load carrying capacity has been reduced by a measurable amount. Since the vibration characteristics of structures are functions of these properties, then damage is accompanied by changes in these characteristics. Thus, in principle, if the resonant frequencies and mode shapes are measured before and after a damage, it is possible to solve an inverse problem to determine the changes in these mechanical properties (element stiffness and masses). These changes thus provide an indication of the location and magnitude of the damage.

Modal testing as a means of inspection has several advantages. Direct exposure of structural elements is not required, and at the same time more of the complete structure can be inspected in one modal test by having appropriately placed sensors. In contrast with visual inspection and instrumental evaluation techniques which basically are local assessments, vibration-base methods rely on measurements of the global dynamic properties of structures to detect and quantify damage. The consequences of this are a reduction in schedule and cost. The damaged regions might be identified by performing an on-orbit modal test using the spacecraft reaction control system to excite the structure and produce modal response characteristics such as frequencies and mode shapes. These parameters are then compared to a baseline set of parameters. A variety of algorithms have been proposed that will trace differences in the two sets of data to specific or likely damaged locations. Some of these techniques include modal residual force methods, optimal matrix update method, sensitivity methods, eigenstructure assignment method, damage index method, system-identification based method, flexibility method, strain distribution method, strain energy method, and intelligence-based methods, such as artificial

neural network and pattern recognition. All these techniques have their strengths and limitations in their abilities to correctly detect, locate and quantify damage in structures using changes in vibrational characteristics. In addition, the requirements of each different techniques are different, for example, some require the extraction of modal responses over a wide frequency band; while other methods only require the measurement of a few resonant frequencies and mode shapes. Some methods also require the measurement of complete mode shapes; while others utilize realization of the modes at a few points. A lot of approaches are severely limited with the assumption that the system mass is constant and changes in vibration characteristics are associated with only stiffness variations. This might be unrealistic for large flexible space structure, where frequency shifts can be expected to occur as a result of mass variations associated with the movement of antenna, astronauts, and solar arrays; ducking of visiting spacecraft; or changing levels in fluid containers. Therefore, some methods account for changes to both mass and stiffness.

Before conducting damage assessment, a refined baseline finite element model of the original structure must be developed, considering the modeling error, fabrication-induced errors, uncertainty in the structural parameters, and instrumentation errors. Modification of a structural finite element model such that the FEM eigensolution matches the results of a modal vibration experiment is called model refinement, or model update technique, or in more general term, called system identification. The motivation behind the development of FEM refinement techniques is based on the need to "validate" analytical FEM before its acceptance as the basis for final design analysis. Performing the first-stage modal testing on a structure will correlate and calibrate the structure's analytical model in order that mode shapes and frequencies of the model and test results agree over selected frequency ranges. The resulting model contains a more accurate representation of the dynamics of the real structure. A vast amount of work has been done in this area. But, in order to use system identification in damage detection, more strict formulation must be provided, for example, maintaining element connectivity and sparsity, preservation of symmetry and positive definiteness.

After the first-stage modal updating, i.e., setting up the baseline model, the refined finite element model is considered as the accurate representative of the original undamaged structure. Any further changes in vibrational signature at some later time will be considered as the damage-induced discrepancy. The damaged model, along with the updated finite element model, will be used in the damage localization process. This process searches for the structural property matrices such as stiffness and mass matrices that maintain the zero-non-zero pattern of the updated matrices, and thus do not introduce unrealistic load paths, while reproducing the modes observed during the test. This is almost a repetition of the first-stage system identification process except that instead of updating the analytical model with the new information, the process seeks out the elements of the stiffness matrix and/or mass matrix that change the most in order to produce the observed results. Once these matrix elements have been identified, a physical map of the geometry can be used to determine which elements of the structure are most likely contributors to the changes due to damage. The majority of algorithms used to address the FEM refinement and/or damage detection can be broadly classified as follows.

(1) Modal Residual Force Method: which is the most straightforward method among the vibrational assessment methods for structural damage detection. Identifying the location of damage in the structure is based on differences in eigenvalues of the pre-damage structure (represented by a refined finite element model) and the post-damage structure. In concept, the

natural frequencies and mode shapes of the damaged structure must satisfy an eigenvalue equation. For the *ith* mode of the potentially damaged structure, the corresponding eigenvalue equation should be $\left(K_d - \lambda_{d_i} M_d\right)\phi_{d_i} = 0$, where K_d and M_d are the unknown stiffness and mass matrices associated with the damaged structure, and $\lambda_{d_i} = \omega_{d_i}^2$ is the experimentally measured eigenvalue (natural frequency squared) corresponding to the experimentally measured *ith* mode shape ϕ_{d_i} of the damaged structure. Assuming that the stiffness and mass matrices associated with the damaged structure are defined as $K_d = K_a + \Delta K$ and $M_d = M_a + \Delta M$, where K_a and M_a are the analytical refined baseline stiffness and mass matrices, and ΔK and ΔM are the unknown changes in the stiffness and mass matrices as a result of damage. Then, the eigenvalue equation for the damaged structure can be written as $\left(K_a - \lambda_{d_i} M_a\right)\phi_{d_i} = -\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i}$. The right-side term is defined as the **modal residual force vector** for the *ith* mode of the damaged structure, and designated as $R_i = -\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i}$, which is the error resulting from the substitution of the refined analytical FEM and the measured modal data into the structural eigenvalue equation. The left-side term is known, so is the modal residual force vector, and will equal to zero only if $\left(\lambda_{d_i}, \phi_{d_i}\right)$ are equal to the undamaged baseline values $\left(\lambda_{a_i}, \phi_{a_i}\right)$. Regions within the structure that are potentially damaged correspond to the degrees of freedom that have large magnitudes in R_i. Using the definition of the modal residual force vector R_i, the eigenvalue equation of the damaged structure can be written as $-\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i} = R_i$. Since the terms inside of the parentheses contain the unknown changes in stiffness and mass matrices due to damage, it is desirable to rewrite it as $[C]\{\varepsilon\} = \{Z_i\}$, where, $\{\varepsilon\}$ is the unknown vector of the changes in stiffness and mass matrices containing only the terms appearing in the *jth* equation for which $R_i(j) \neq 0$. $\{Z_i\}$ is the vector consisting of the nonzero terms of R_i, and $[C]$ the coefficient matrix consisting of the measured eigenvector parameters. If the measured modes are exact, the equation then provides the exact $\{\varepsilon\}$ vector. However, the number of measured modes which are needed for solving this equation is increasing with the number of dof's of the ends of the damaged zone.

Ricles and Kosmatka presented a methodology for detecting structural damage in elastic structures based on residual modal force method. Measured modal test data along with a correlated analytical structural model are used to locate potentially damaged regions using residual modal force vectors and to conduct a weighted sensitivity analysis to assess the extent of mass and/or stiffness variations. The approach accounted for the variations in system mass, stiffness, and mass center location; and perturbations of both the natural frequencies and mode shapes; statistical confidence factors for the structural parameters and potential experimental instrumentation error. Sheinman developed a closed-form algorithm for precise detection using test data and likewise preserving the connectivity. This algorithm identifies the damaged degree of freedom, and then solves a set of equations to yield the damaged stiffness coefficients. Its drawback is that even a small number of damaged dof's may result in a large number of damaged stiffness coefficients with the corresponding excessive measurement volume. He then presented an algorithm which preserves the "ratio of stiffness coefficients" besides the connectivity, and thus significantly reduces the needed measurements. The algorithm identifies the damaged members through very few measured modes, and is suitable for large structures with thousands of dof's.

(2) Optimal Matrix Update: which is arguably the largest class of FEM refinement algorithms to date. The essence of the method is to solve a closed-form equation for the matrix perturbations which minimize the residual modal force vector, or constrain the solution to satisfy it. Typically, an updating procedure seeks stiffness and/or mass correction matrices ΔK and/or ΔM such that the adjusted model $\{(K+\Delta K); (M+\Delta M)\}$ accurately predicts the measured quantities. Computing the matrix perturbations, which eliminate the residual modal force, is often an underdetermined problem, since the number of unknowns in the perturbation set can be much larger than the number of measured modes and the number of measurement degrees of freedom. In this case, the property perturbations, which satisfy the residual modal force equation, are non-unique. Thus, optimal matrix update methods apply a minimization to the property perturbation to select a solution to the residual modal force equation subject to constraints such as symmetry, positive definiteness, and sparsity. This minimization applies to either a norm or the rank of the perturbation property matrix or vector. In general, the eigenvalue equation for the damaged structure can be written as $\left(-\lambda_{d_i} M_a + j\lambda_{d_i} D_a + K_a\right)\phi_{d_i} = -\left(-\lambda_{d_i}\Delta M + j\lambda_{d_i}\Delta D + \Delta K\right)\phi_{d_i}$. The right-side

term is the residual modal force vector $R_i = -\left(-\lambda_{d_i}\Delta M + j\lambda_{d_i}\Delta D + \Delta K\right)\phi_{d_i}$. The left-side term is known, and can be designated as E_i, so the eigenvalue equation can be written as $\left(-\lambda_{d_i}\Delta M + j\lambda_{d_i}\Delta D + \Delta K\right)\phi_{d_i} = E_i$, or, $[\Delta A]\phi_{d_i} = E_i$ where $[\Delta A] = \left(-\lambda_{d_i}\Delta M + j\lambda_{d_i}\Delta D + \Delta K\right)$. Conceptually, various optimal matrix update methods can be described as follows. First, *the minimum-norm perturbation* of the global matrices can be summarized as $MIN\|[\Delta A]\|$ subject to the constraint of the eigenvalue equation, also, the constraints of symmetry and sparsity of the matrix $[\Delta A]$. Constrainting the aparsity to be the same as the analytical FEM has the effect of ensuring that no new load paths are generated by the updated model. This approach was used by Baruch and Itzhack, Berman and Nagy, Kabe, and Smith and Beattie. Second, *the minimum-rank perturbation* of the global matrices can be summarized as $MIN\{RANK([\Delta A])\}$ subject to the same

constraints as those in the first approach. Kaouk and Zimmerman used this approach. Third, *the minimum-norm, element-level update procedures* presented by Chen and Garba and Li and Smith incorporated the connectivity constraint between the element-level stiffness parameters and the entries in the global stiffness matrix directly into the eigenvalue equation to get

$\frac{\partial}{\partial p}\left([\Delta A]\phi_{d_i}\right)\{\Delta p\} = E_i$, which is then solved for minimum-norm of $\{\Delta p\}$. Doebling provided a

detailed derivation of the minimum rank elemental parameter update approach.

The majority of the early work in optimal matrix update used the minimum norm perturbation of the *global stiffness matrix*. The correction matrices are usually constructed at the *global level* through the constrained minimization of a given weighted functional. The motivation for using this objective function is that the desired perturbation is the one which is the "smallest" in overall magnitude. But, a common drawback of the methods is that the computed perturbations are made to stiffness matrix values at the structural DOF, rather than at the element stiffness parameter level. However, such an optimization may yield updated matrices where the symmetry and orthogonality conditions as well as the original connectivity are destroyed. Penalty techniques and Lagrangian multipliers are then often required to enforce these constraints, which undoubtfully increases the computational effort. Moreover, a global updating of the FEM matrices is useful only if corrections bring the understanding of what truly differs between the real

structure and its modeling. With global adjustment schemes, this physical meaning is usually difficult to interpret, which makes damage prediction hazardous. In order to keep the symmetry, positive definiteness, and connectivity properties, or keep the original load pathes uncorrupted, an *element-by-element parameter based updating method* should be considered. Once the FEM has been adjusted, changes in the physical parameters of the system are available at the element level, which greatly facilitates the understanding of modeling errors or damage locations. Computing perturbations at the elemental parameter level uses the sensitivity of the entries in the stiffness matrix to the elemental stiffness parameters so that the minimum-norm criterion can be applied directly to the vector of elemental stiffness parameters. The resulting update consists of a vector of elemental stiffness parameters that is a minimum-norm solution to the optimal update equation. There are three main advantages to computing perturbations to the elemental stiffness parameters rather than to global stiffness matrix entries: (1) The resulting updates have direct physical relevance, and thus can be more easily interpreted in terms of structural damage or errors in the FEM; (2) The connectivity of the FEM is preserved, so that the resulting updated FEM has the same load path set as the original one; and (3) A single parameter, which affects a large number of structural elements can be varied independently.

Early work in optimal matrix update using measured test data was performed by Rodden, who used ground vibration test data to determine the structural influence coefficients of a structure. Brock examined the problem of determining a matrix that satisfied a set of measurements as well as enforcing symmetry and positive definiteness. Berman and Flannelly discussed the calculation of property matrices when the number of measured modes is not equal to the number of DOF of the FEM. Several optimal matrix update algorithms are based on the problem formulation set forth by Baruch and Bar Itzhack. In their work, a closed-form solution was developed for the minimal Frobenius-Norm matrix adjustment to the structural stiffness matrix incorporating measured frequencies and mode shapes. Berman and Nagy adopted a similar formulation but included approaches to improve both the mass and stiffness matrices. In the previously cited work, the zero/nonzero (sparsity) pattern of the original stiffness matrix may be destroyed. Algorithms by Kabe, Kammer, and Smith and Beattie have been developed which preserve the original stiffness matrix sparsity pattern, thereby preserving the original load paths of the structural model. The Kabe algorithm utilizes a percentage change in stiffness value cost function and appends the sparsity pattern as an additional constraints; whereas Kammer and Smith and Beattie investigate alternate matrix minimization formulations. Smith and Hendricks have utilized these various matrix updates in direct studies of damage location in large truss structures. Although minimization of the matrix norm of the difference between the original and refined stiffness matrix is justified for the model refinement case, its applicability for damage detection is open to question because damage typically results in localized changes in the property matrices; whereas the matrix norm minimization would tend to "smear" the changes throughout the entire stiffness matrix.

(3) Sensitivity Methods: which make use of sensitivity derivatives of modal parameters such as modal frequencies and mode shapes with respect to physical structural design variables such as element mass and stiffness, section geometry, and material properties, to iteratively minimize the residual modal force vector. The derivatives are then used to update the physical parameters. These algorithms result in updated models consistent within the original finite element program framework. The residual modal force vector is defined as $R_i = -\left(-\lambda_{d_i} \Delta M + \Delta K\right)\phi_{d_i} = \left(K_a - \lambda_{d_i} M_a\right)\phi_{d_i}$,

where the rightmost term is known and will be equal to zero for an undamaged structure. Assume that the selected measured vibrational characteristics are contained in a vector, $\Lambda^T = \{\omega^2, \phi\}^T$; Λ_a and Λ_d correspond to the analytical refined structural model and damaged structural model, respectively. The unknown structural parameters in damaged region are contained in a vector r; r_a and r_d correspond to the analytical refined structural model and damaged structural model, respectively. The relationship between these vectors can be established by using a first-order Taylor series expansion, $\Lambda_d = \Lambda_a + T(r_d - r_a) + \varepsilon$, where, ε is a vector of measurement errors associated with each measured parameter, such as natural frequencies and mode shape amplitudes. Matrix T is a *sensitivity matrix* that relates modal

parameters and the physical structural design variables, $T = \begin{bmatrix} \dfrac{\partial \omega^2}{\partial K} & \dfrac{\partial \omega^2}{\partial M} \\ \dfrac{\partial \phi}{\partial K} & \dfrac{\partial \phi}{\partial M} \end{bmatrix}_a \begin{bmatrix} \dfrac{\partial K}{\partial r} \\ \dfrac{\partial M}{\partial r} \end{bmatrix}_a$. The subscript

"a" is associated with the analytical baseline configuration, which means that the derivatives are determined from the analytical baseline data Λ_a and r_a. The four individual submatrices in the first matrix of T represent partial derivatives of the eigenvalues and mode shapes with respect to the coefficients of the stiffness and mass matrices, whereas the second matrix of T represents the partial derivatives of the stiffness and mass matrices with respect to the structural parameters r. For mode k and considering measurement points i and j, it can be shown,

$$\frac{\partial \omega_k^2}{\partial K_{ij}} = \frac{\phi_{ik}\phi_{jk}}{\phi_k^T M \phi_k} \; ; \qquad \frac{\partial \phi_{rk}}{\partial K_{ij}} = \sum_{n=1}^{q} \left[\frac{\phi_{in}\phi_{jk}\phi_{rn}}{(\omega_k^2 - \omega_n^2)\phi_n^T M \phi_n} \right](1 - \delta_{nk})$$

$$\frac{\partial \omega_k^2}{\partial M_{ij}} = \frac{-\omega_k^2 \phi_{ik}\phi_{jk}}{\phi_k^T M \phi_k} \; ; \qquad \frac{\partial \phi_{rk}}{\partial M_{ij}} = \sum_{n=1}^{q} \left[\frac{-\omega_k^2 \phi_{in}\phi_{jk}\phi_{rn}(1 - \delta_{nk})}{(\omega_k^2 - \omega_n^2)\phi_n^T M \phi_n} - \frac{\phi_{in}\phi_{jk}\phi_{rn}\delta_{nk}}{2\phi_n^T M \phi_n} \right]$$

where, n is the mode number, and q is the number of retained modes in Λ_a for assessment. The goal is to determine r_d; the components of r_d include the elements in ΔK and/or ΔM in the expression of the residual modal force vector. Direct application of nonlinear optimization to the damage detection problem has been studied by Kajela and Soeiro and Soeiro. In this technique, it is required that the physical design variables be chosen such that the properties of the damaged component can be varied. This presents a practical difficulty in that the number of design variables required may grow quite large, although techniques utilizing continuum approximations are discussed as one possible solution to decrease the number of design variables.

(4) Control-Based Eigenstructure Assignment Techniques: which design a controller, known as the "*pseudo-control*", that minimizes the residual modal force vector. The controller gains are then interpreted in terms of structural parameter modifications. The pseudo-control produces the measured modal properties with the initial structural model, and is then translated into matrix adjustments applied to the initial FEM. Inman and Minas discussed two techniques for FEM refinement. The first assigns both eigenvalue and eigenvector information to produce updated damping and stiffness matrices. An unconstrained numerical nonlinear optimization problem is posed to enforce symmetry of the resulting model. A second approach, in which only eigenvalue information is used, uses a state-space formulation that finds the state matrix that has the measured eigenvalues and that is closest to the original state matrix. Zimmerman and Widengern incorporated eigenvalue and eigenvector information in the FEM using a symmetry preserving

eigenstructure assignment theorem. This algorithm replaces the unconstrainted optimization approach with the solution of a generalized algebraic Riccati Equation whose dimension is defined solely by the number of measured modes. It should be noted that both the sensitivity and eigenstructure assignment algorithms, which do not demand the matrix norm minimization, may prove quite suitable for damage detection.

Zimmerman and Kaouk extended their eigenstructure assignment algorithm to approach the damage location problem better. A subspace rotation algorithm is developed to enhance eigenvector assignability. Because load path preservation may be important in certain classes of damage detection, an iterative algorithm is presented that preserves the load path if the experimental data is consistent. His algorithm begins with a standard structural model with a feedback control, $M\ddot{w} + D\dot{w} + Kw = B_0 u$, where, M, D, and K are the $n \times n$ analytical mass, damping, and stiffness matrices, w is an $n \times 1$ vector of positions, B_0 is the $n \times m$ actuator influence matrix, u is the $m \times 1$ vector of control forces. In addition, the $r \times 1$ output vector y of sensor measurements is given by $y = C_0 w + C_1 \dot{w}$, where, C_0 and C_1 are the $r \times n$ output influence matrices. The control law taken is a general linear output feedback controller, $u = Fy$, where, F is the feedback gain matrix. Rearranging all the equations above, the structural system equation can be written as

$M\ddot{w} + (D - B_0 FC_1)\dot{w} + (K - B_0 FC_0)w = M\ddot{w} + D_a\dot{w} + K_a w = 0$. It's clear that the matrix triple products $B_0 FC_0$ and $B_0 FC_1$ result in changes in the stiffness and damping matrices respectively. These triple products can then be viewed as perturbation matrices to the stiffness and damping matrices such that the adjusted finite element model matches closely the experimentally measured modal properties. Consequently, the changes in the stiffness and damping matrices due to damage can be found. Unfortunately, these perturbation matrices are, in general, non-symmetric when calculated using standard eigenstructure assignment techniques, thus yielding adjusted stiffness and damping matrices that are also non-symmetric. Therefore, a symmetric eigenstructure assignment algorithm is used to determine the refined finite element model of the damaged structure. For the perturbations to be symmetric, the following conditions must be met $B_0 FC_i = C_i^T FB_0^T$, $i = 0, 1$. With the help of a generalized algebraic Ricatti Equation, matrices C_i can then be found, thereby the matrix triple products $B_0 FC_0$ and $B_0 FC_1$ can be computed. In general, the solution will not be unique, two conditions - keeping symmetry and the same definiteness of the original stiffness and damping matrices - will provide help to identify a best solution.

(5) **Damage Index Method:** An important category of vibrational assessment techniques is to use a specially designed **damage index** to indicate the damage location and its extent. The damage index is derived based upon principles in structural dynamics. Lin suggested a type of damage index based on flexibility matrix. The flexibility matrix is determined using experimental data. This matrix is then multiplied by the original stiffness matrix, with those rows and/or columns that differ significantly from a row and/or column of the identity matrix indicating which degrees of freedom have been most affected by the damage. It is then assumed that damage has occurred in structural elements connecting those degrees of freedom. Although this algorithm provides information concerning location of damage, it is difficult to determine the extent of damage. Carrasco suggested another type of damage index based on strain energy. Characterizing the damage as a scalar quantity of the undamaged stiffness matrix, an expression was obtained for element damage factors that quantify the magnitude of the damage for each mode shape. This factor may take values ranging from -1.0 to infinity, where negative values are

13

indicative of potential damage. The most popular damage index is based on a recently developed damage localization theory attributed to Stubbs, et al. This damage localization theory has been utilized to detect and localize the damages in some of civil infrastructures, such as, a real highway bridge on the US Highway *I-40* located in Bernalillo County, New Mexico. The criterion was also applied to the damage detection of an aerospace manipulating system and verified by a computer simulation. Assume that a finite element model of the corresponding structure has been established. The damage index β_j for the *jth* element is given by $\beta_j = \frac{1}{2}\left[\frac{f_{ij}^*}{f_{ij}}+1\right]$, where,

$$f_{ij} = \frac{\int_a^b \left\{\phi_i^{''}(x)\right\}^2 dx}{\int_\Omega \left\{\phi_i^{''}(x)\right\}^2 dx}, \text{ and } f_{ij}^* = \frac{\int_a^b \left\{\phi_i^{''*}(x)\right\}^2 dx}{\int_\Omega \left\{\phi_i^{''*}(x)\right\}^2 dx},$$

and $\phi_i(x)$ is the pre-damage mode shape, $\phi_i^*(x)$ the post-damage mode shape, *i* represents the *ith* mode. The domain Ω includes all elements in the structure concerned, the integration in numerator is implemented over the element *i*. **Damage is indicated at element *j* if $\beta_j > 1.0$.** To avoid possible false indication as a damaged element is at or near a node point of the *ith* mode, the damage index β_j is commonly written as $\beta_j = \frac{1}{2}\left[\frac{f_{ij}^* + 1}{f_{ij} + 1}+1\right]$.

If several modes are used in identification, say, the first *M* modes, then, $\beta_j = \frac{1}{2}\left[\frac{\sum\limits_{i=1}^{M} f_{ij}^* + 1}{\sum\limits_{i=1}^{M} f_{ij} + 1}+1\right]$. The pre-damage mode shape is computed after the finite element model is assembled. The post-damage mode shape must be extracted from the experimental measurements using certain type of system identification method. Because the vibrational characteristics needed for this criterion is mode shapes, time-domain system identification technique is more effective and accurate than those in frequency domain.

(6) System-Identification Based Method: System identification is the name given to the class of problems where the response of a structure is used to determine the system characteristics. In other words, system identification is the process of using a limited number of measurements to identify the natural frequencies and mode shapes of the structure, and to update the analytical model of the system to duplicate the measured response. This analytical model can then be used to predict the structural response to future inputs. There are seemingly infinite number of system identification methods that have been developed. What type of system identification method should be selected depends on what type of structure is in concern, and what purpose a particular system identification method works for. For large aerospace structures, for example, damping is small, so proportional damping can be assumed in some instances, and damping can be neglected entirely in others. Also, these large structures typically have low, closely spaced frequencies which can present problems for some identification methods. Those characteristics provide the basis for narrowing the field of system identification methods. But, for most system identification methods and their applications, following common assumptions are usually included. The structural response is assumed to be linear, so that the theory of superposition holds. The situation is considered to be stationary, so that the parameters are constants, not time varying. Also, the model of the system is considered to be deterministic, so that stochastic analysis are not necessary.

14

Selecting a method of system identification for damage detection can be a significant task. One approach to the problem of damage detection is the determination of areas of reduced or zero stiffness in the structure. System identification methods that focus on the stiffness properties would then be considered for this approach. The stiffness properties for a structure are represented in various ways depending on the modeling technique. Physical parameters (such as elastic modulus in a continuous model of structure) are used in some model; while non-physical parameters (such as an element of the stiffness matrix that results from a finite element model of the structure) are identified in many other methods. Therefore, the model of the structure becomes a major contributor in selecting system identification methods for damage detection.

Two methods which identify non-physical parameters for discrete model are the stiffness matrix adjustment method and matrix perturbation method. White and Maytum's matrix perturbation method uses linear perturbation of submatrices and an energy distribution analysis as the basis to determine the changes in the elements of the global stiffness and mass matrices. The implementation of this method is considerable time consuming. The selection of submatrices requires an intuition or prior experience. Therefore, it is less suitable for damage detection. Kabe's method used an initial estimate of the stiffness matrix, the known mass matrix, a limited set of measured modal data, and the connectivity of the structure to produce an adjusted stiffness matrix. Therefore, this method identifies nonphysical parameters, i.e. the elements of the stiffness matrix. Kabe used a so-called "scalar matrix multiplication operator $\otimes$", for which two matrices are multiplied, element by element, to produce a third matrix. This matrix multiplication operator provides that zero elements in the original stiffness matrix can not become non-zero elements in the final result. Each element of the adjusted stiffness matrix $[K_d]$ is the product of the corresponding elements of the original stiffness matrix $[K_a]$ and an adjustment matrix $[\gamma]$ as follows, $[K_d] = [K_a] \otimes [\gamma]$, that is, $K_{d_{ij}} = K_{a_{ij}} \gamma_{ij}$. A constrained optimization procedure is developed to minimize the percentage of each stiffness element. The error function used represents the percentage change of each stiffness matrix element, while constraints are provided from the modal analysis equations and the symmetry property of the stiffness matrix. Lagrange multipliers $[\lambda]$ are used to expand the error function to include the constraints. The resulting optimization procedure is used to solve the Lagrange multipliers. Once the Lagrange multipliers $[\lambda]$ are known, the adjusted stiffness matrix $[K_d]$ can be obtained from the original stiffness matrix $[K_a]$ and the mode shape function $[\phi]$: $[K_d] = [K_a] - \frac{1}{4}([K_a] \otimes [K_a]) \otimes ([\lambda][\phi]^T + [\phi][\lambda]^T)$. Kabe prodides an identification method for stiffness matrix elements that does not have the problem of unrealistic couplings in result. If the adjustment in stiffness matrix was resulted from structural damage, it is clear that Kabe's method can be used to identify the damaged elements. For the situation that some elements of the original global stiffness matrix are zeros where a physical coupling does exist, Kabe's method failed to detect the damage in some of the elements. Those zeros result from that the contribution from one member cancels the contribution from another in the global assembly. When one of these members is lost function due to damage, the zero value in the original undamaged stiffness matrix becomes a non-zero value in the damaged stiffness matrix. Kabe's method is restricted, by design, so that zero values can not be adjusted to non-zero values. Therefore, these elements of the damaged stiffness matrix can not be correctly identified.

Peterson et al. presented a method for detecting damage based on the comparison of mass and stiffness matrices measured prior to damage with those after the damage, rather than the comparison of respective modal parameters. An advantage of this method is that the data which

15

are compared directly indicate the presence or absence of damage. This means that no nonlinear programming problem is involved, nor is a finite element model of the structure required. The approach is based on an algorithm for transforming a state-space realization into a second order structural model with physical displacements as the generalized coordinates. The first step is to form a state-space input-output model of the structure using a model realization procedure, such as the Eigensystem Realization Algorithm (ERA). Next, the state-space model is transformed into modal coordinates, and the mass-normalized modal vectors are determined for the output measurement set using the Common Basis Structural Identification algorithm. The physical mass, damping and stiffness matrices are then synthesized by determining the Schur complement of the global coordinate model. By repeating the model synthesis after damage has occured, it is possible to generate new mass and stiffness matrices of the damaged structure. An element-by-element comparison of the mass and stiffness matrices of the two models directly locates and quantifies changes in the mass and stiffness due to the damage.

(7) **Flexibility Method**: In general, structural damage can be viewed as a reduction of stiffness. Corresponding to such a reduction in stiffness, the flexibility of a damaged member is increased. In some instances, however, additional elements are not reflected by adding additional stiffness matrix since such elements will not increase, but decrease the global stiffness of the structure. That is, instead of additional stiffness, but additional flexibility is added to the structure. In order to account for the special problems arising from the addition of flexibility to a structure, non-destructive damage detection method using flexibility formulation has been considered. Topole's method[49] can be summarized as follows. The eigenvalue equation of a linear structural system is $\left(K - \lambda_i M \right) \phi_i = 0$. Using $A = K^{-1}$, which is the *flexibility matrix* of the structure, to substitute K,

and pre-multiplying above equation with ϕ_i^T yields $\dfrac{1}{\lambda_i} \phi_i^T \phi_i = \phi_i^T A M \phi_i$. For the damaged structure,

the same equation holds, $\dfrac{1}{\lambda_{d_i}} \phi_{d_i}^T \phi_{d_i} = \phi_{d_i}^T A_d M_d \phi_{d_i}$, where, $A_d = A + \Delta A$, and $M_d = M + \Delta M$. Assume

that there is no change in mass, i.e. structural damage is reflected only by changes of the flexibility

matrix. Then, the above equation reduces to $\dfrac{1}{\lambda_{d_i}} \phi_{d_i}^T \phi_{d_i} = \phi_{d_i}^T A\ M\ \phi_{d_i} + \phi_{d_i}^T \Delta A\ M\ \phi_{d_i}$. Dividing this

equation by the undamaged eigenvalue equation, and rearranging the terms results in

$$\frac{\phi_{d_i}^T \Delta A\ M\ \phi_{d_i}}{\phi_i^T A\ M\ \phi_i} = \frac{\lambda_i}{\lambda_{d_i}} \frac{\phi_{d_i}^T \phi_{d_i}}{\phi_i^T \phi_i} - \frac{\phi_{d_i}^T A\ M\ \phi_{d_i}}{\phi_i^T A\ M\ \phi_i}.$$ Defining ΔA_j as the contribution of the *j*th element to ΔA,

and expressing ΔA_j in terms of a product of a scalar factor β_j representing the relative damage in element *j*, and the contribution of the *j*th element to the initial undamaged flexibility matrix A_j, i.e., $\Delta A_j = \beta_j A_j$, then, the above equation can be written as

$$\sum_{j=1}^{n} \frac{\phi_{d_i}^T \left(\beta_j A_j \right) M\ \phi_{d_i}}{\phi_i^T A\ M\ \phi_i} = \frac{\lambda_i}{\lambda_{d_i}} \frac{\phi_{d_i}^T \phi_{d_i}}{\phi_i^T \phi_i} - \frac{\phi_{d_i}^T A\ M\ \phi_{d_i}}{\phi_i^T A\ M\ \phi_i}.$$ Designating the right-hand side as Z_i, i.e.,

$$Z_i = \frac{\lambda_i}{\lambda_{d_i}} \frac{\phi_{d_i}^T \phi_{d_i}}{\phi_i^T \phi_i} - \frac{\phi_{d_i}^T A\ M\ \phi_{d_i}}{\phi_i^T A\ M\ \phi_i}, \text{ and } F_{ij} = \frac{\phi_{d_i}^T A_j M\ \phi_{d_i}}{\phi_i^T A\ M\ \phi_i}$$ which can be viewed as an element of the

sensitivity matrix F, describing how the *ith* modal parameters are affected by changes in the flexibility of the element *j*. A new equation, $F \cdot \beta = Z$, is then produced, where F-matrix shows

how the modal parameters are sensitive to changes in the element flexibilities. Structural damage, or changes in the flexibilities of the elements, could now be determined by computing the sensitivity matrix F and the residual modal force vector Z, and then solving the set of linear equations for the unknown vector β. Note that damage is generally indicated by a reduction in stiffness which means an increase in flexibility. Thus, structural damage will be denoted by positive value of β_j.

(8) Strain Distribution Method: which measures changes in strain distribution from normal strain distribution patterns to assess structural damage. The concept is to detect common failure modes by strain and/or acoustic emission measurements. Strain measurement can be used to detect most of failure modes. Strain history in metallics can also be used for prediction of the remaining structural life. This type of methods has difficulty in assessing composite delamination. Delamination in a composite structure will show a measurable change in strain only when it becomes unstable in compression. Because the failure can become catastrophic at this point, strain measurement is unacceptable. Acoustic stress waves emanating from a delaminated area could potentially be distinguished from the healthy structure in a real-time environment. Strain distribution sensitivity to damage is basic to a strain-based damage detection method. This sensitivity is studied analytically using finite element models. Sensitivity studies were conducted to define the measurement density required to sense a precritical flaw.

Ott reported that normalized strain distribution was used to determine damage on a LTV A-7 wing model by comparing baseline distributions to distributions where damage was present. Theoretical measurements could be taken to determine the exact flight data, and compared with strain measurements to determine the damage. The damaged structural strain distribution has two recognizable attributes. The first is the relatively rapid change in slope in the curve indicating damage. The second is that the damage curve falls outside the normal strain envelope. The second attribute, that is, the recognition of the damaged strain excursion outside the undamaged envelope, is most useful for damage detection. This approach greatly simplifies the total data requirements by eliminating exact flight data identification.

(9) Strain Energy Method: Strain energy distribution has been used by previous researchers as an important measure in work related to structural damage detection. The investigations of these work suggest that modal data contain sufficient information to identify damage only if the damaged member's contribution of its strain energy is a significant part of the strain energy of the modes being measured. A member with higher strain energy in a certain modal set stores a fair amount of energy for this particular modal set, that is, that member carries a non-negligible share of the overall loading. Thus, any modification of its material and/or geometrical properties affects the overall dynamics of the structure. It is common therefore to assume that the identified modes which are used in the damage detection algorithm should store a large percentage of their strain energy in the members where potential damage might occur. Carrasco directly used modal strain energy for localization and quantification of damage in a space truss model. The method considers the mode shapes of the structure pre- and post-damage measured via modal analysis. Values of the mode shapes at the connections are used to compute the strain energy distribution in the structural elements. Characterizing the damage as a scalar quantity of the undamaged stiffness matrix, an expression was obtained for element damage factors that quantify the magnitude of the damage for each mode shape. The total modal strain energy for the *jth* mode can be computed using the expression, $U_j = \frac{1}{2}\phi_j^T K \phi_j$, which can also be considered as the sum of

the strain energy in all the structural elements, $U_j = \sum_{i=1}^{n} U_{ij} = \frac{1}{2}\sum_{i=1}^{n} \phi_{ij}^T K_i \phi_{ij}$, where U_{ij} is the modal

strain energy contribution of the *ith* element to the *jth* mode. Damage brings changes in element strain energy between the undamaged and damaged structures around the vicinity of the damage. These differences can be computed by $\Delta U_{ij} = U_{ij} - U_{d_{ij}} = \frac{1}{2}\phi_{ij}^T K_i \phi_{ij} - \frac{1}{2}\phi_{d_{ij}}^T K_{d_i}\phi_{d_{ij}}$. Assuming that the nominal undamaged properties of the element be used to approximate the damaged properties of

the same element, then, a damage factor α_{ij} can be defined as $\alpha_{ij} = \frac{U_{ij}}{U_{d_{ij}}} - 1 = \frac{\phi_{ij}^T K_i \phi_{ij}}{\phi_{d_{ij}}^T K_i \phi_{d_{ij}}} - 1$, which

quantifies the damage for element i using mode j. This factor may take values ranging from *-1.0* to infinity, where negative values are indicative of potential damage. Practically, the computation of α_{ij} might bring some numerical difficulties. For the following cases, numerical problems may occur: (1) when damage is evaluated at an element that has little or no modal strain energy content for the corresponding mode in the undamaged and/or damaged states; (2) when the induced damage is large, the redistribution of modal strain energy may be so severe that elements with significant energy content in the undamaged state may have little or no energy content in the damaged state.

(10) Artificial Intelligence-Based Methods: Application of the methedology in Artificial Intelligence (AI) field to structural damage evaluation has increased significantly during the last decade. Among others, Pattern Recognition and Neural Network are two popular examples. The mathematical approaches to pattern recognition may be divided into two general categories, namely, the syntactic (or, linguistic) approach and the decision theoretic (or, statistical) approach. The majority application of the pattern recognition method to structural failure detection and diagnostics has been the decision theoretic approach. This is a process that is generally used to digest a vast amount of data, reduce it into a meaningful representation, and make decision on the outcome of the observation data using a classifier. Grady applied this approach to an in-flight airframe monitoring system. A personal computer-based pattern recognition algorithm could be "trained" using laboratory test data, to recognize such characteristic changes in structural vibrations, and to infer from those changes the type and extent of damage in a structural component. For example, as damage develops, a loss in structural stiffness causes a corresponding decrease in the resonant frequencies of the structure, causing the frequency response curve to shift along the frequency axis. These shifts in frequencies are related to damage characteristics during the training phase. With sufficient training input, the pattern recognition algorithm can relate typical waveform characteristics to structural damage levels. In general, four fundamental steps are required to "train" the pattern recognition algorithm: pattern measurements; feature extraction; learning; and classification. After a set of features (e.g., frequencies, damping properties) are calculated that characterize the pattern measurements (vibration signals), the classifier partitions the feature space into a number of regions, and associates each region with one of the known outcomes (e.g., damage levels). Decision making ability is established through a learning process which compiles and retrieves information based on experiences where a priori knowledge of an outcome has been established.

The basic idea of neural network application is to "train" the network with known sets of structural vibration test data, and use the network to predict or identify the structural characteristics under other operating conditions. Ganguli et al have developed a neural network

model to characterize the effect of damage conditions in rororcraft structure. Rosario, et al applied neural technique to the damage assessment of composite structure. Although neural network has many merits, it is limited to detecting only forms of damage that have been trained into the neural network. In addition, large amounts of data and time are required to train the network to learn the system model.

5. Funding Expenditure Report

Account Description	Allotment Amount in the Budget	Actual Spending
1. Faculty salary	$7,998	$7,998
2. Student salary	$3,500	$3,500
3. Fringe benefit	$2,187	$2,187
4. Indirect cost	$6,324	$6,324
5. Travel	$4,500	$3,627
6. References and supplies	$491	$1,364
Total Budget	**$25,000**	**$25,000**

6. Concluding Remarks:

Adding a new module in NASA's existing automated diagnostic system to monitor the healthy condition of rocket engine structures is a crucial task. The reasons are clear. First, complexity in structures, geometry, and material composition makes it impossible to predict structural anomaly analytically. Second, the rigorous structural design specification makes possibilities to overstress the rocket engine structures so that there is a high probability that damage is incurred in engine's structural components during or after engine's operation. Third, the hazardous working condition threatens the safety of the engine structures.

Non-destructive damage detection is an important issue in almost all structural areas ranging from aerospace/aeronautical structures, civil infrastructures, and structural materials. The use of vibrational-based nondestructive evaluation techniques to locate structural damage has been attempted to evaluate the integrity of civil infrastructures, such as highway bridges, offshore-oil and gas platforms, composite laminates, continuum structures, and especially aircraft and large space structures. In an attempt to develop a structural health monitoring system for rocket engines, more than one hundred technical papers in the vibrational assessment area have been searched and briefly reviewed during the grant period. A comprehensive overview of various vibrational-based nondestructive evaluation techniques has been presented in our recent paper, including a brief introduction of the theoretical background of different methods, an analysis of their advantages and drawbacks, and a foresight of the applications of different methods towards different type of structures. To date most research into vibrational-based structural damage detection has been performed by a handful of researchers at a wide variety of sites with little or no coordination in research efforts. Many of these methods have been tested using mass-spring test models or simple planar truss models. Few of standard test problems truly embrace the essence of

real-world structures and as such poor judges of the performance of a few method. There clearly is a gap between theoretical research and practical application. No one vibrational-based method has been successfully used in any real-world non-destructive structural damage diagnosing and monitoring system. The use of vibrational-based nondestructive evaluation techniques to locate structural damage has been attempted to evaluate the integrity of civil infrastructures, such as highway bridges, offshore-oil and gas platforms, composite laminates, continuum structures, and especially aircraft and large space structures. Few researches, however, have been contributed to the application of such techniques to the rocket engine structures.

We strongly recommend, after the first-stage investigation, that the proposed research task to develop a structural health diagnostic and monitoring system for rocket engines be continued.

Appendix I - A Technical Paper

Shen, J.Y., Sharpe, L., Jr. and Jankovsky, A.L., "**An Overview of Vibrational-Based Nondestructive Evaluation Techniques**", Prceedings of the International Symposium on Non-Destructive Damage Evaluation (NDE) of Aging Infrastructure and Aging Aircraft, Airport, and Aerospace Hardware, San Antonio, Texas, March 31 - April 2, 1988, pp.117-128.

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An Overview of Vibrational-Based Nondestructive Evaluation Techniques

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ABSTRACT

Non-destructive damage detection is an important issue in almost all structural areas ranging from aerospace/aeronautical structures, civil infrastructures, and structural materials. The use of vibrational-based nondestructive evaluation techniques to locate structural damage has been attempted to evaluate the integrity of civil infrastructures, composite laminates, continuum structures, and especially aircraft and large space structures. In an attempt to develop a structural health monitoring system for rocket engines, hundreds of technical papers in the vibrational assessment area have been reviewed. This paper provides a comprehensive overview of various vibrational-based nondestructive evaluation techniques, including a brief introduction of the theoretical background of different methods, an analysis of their advantages and drawbacks, and a foresight of the applications of different methods towards different type of structures. To date most research into vibrational-based structural damage detection has been performed by a handful of researchers at a wide variety of sites with little or no coordination in research efforts. Many of these methods have been tested using mass-spring test models or simple planar truss models. Few of standard test problems truly embrace the essence of real-world structures and as such poor judges of the performance of a few method. There clearly is a gap between theoretical research and practical application. This paper would be considerably helpful for future research, and especially beneficial for the development of a structural monitoring system in choosing an applicable and realistic method as a basis.

Key Words: Nondestructive Evaluation; Vibrational-Based Assessment; Structural Damage Localization; Structural System Health Monitoring.

1. INTRODUCTION

NASA has initiated an effort to develop a generic post-test/post-flight diagnostic system for rocket engines[1]. The ability to automate the functions performed by the engineers would benefit both current and future rocket engines. So far the automated diagnostic system has not functioned for detection of potential damages in the rocket engine structures. In reality, however, adding a module in the automated diagnostic system to monitor the healthy condition of rocket engine structures is a crucial task. The rigorous structural design specification, non-analytical predictable structural anomaly, and hazardous working conditions are all bringing the necessity of frequent inspections of the structural components after an engine has been flown or tested. Toward this end, a new module, which functions as a non-destructive structural damage diagnosing and monitoring sub-system, has been suggested to be added and consistent with the existing NASA's automated diagnostic system. The function of this sub-system is to detect damage as it is incurred by the engine structures, determine the location and extent of the damage, predict whether and when catastrophic failure of the structure will occur, and alert the operators as to how the performance of the structure is affected so that appropriate steps can be made to remedy the situation.

In an attempt to develop a structural health monitoring system for rocket engines, hundreds of technical papers in the vibrational assessment area have been reviewed. This paper provides a comprehensive overview of various vibrational-based nondestructive evaluation techniques, including a brief introduction of the theoretical background of different methods, an analysis of their advantages and drawbacks, and a foresight of the applications of different methods towards

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different type of structures. The technique to identify damage in principle utilizes the changes in the vibration signature (natural frequencies and mode shapes) due to damage. As damage accumulates in a structure, the structural parameters (stiffness, damping, and mass) change. The changes in structural parameters, if properly identified and classified, can be used as quantitative measures that provide the means for assessing the state of damage of the structure. The problem is always formulated as given the changes in the vibrational characteristics before and after the damage, determine the location, magnitude and the type of damage. A number of techniques for vibrational-based non-destructive damage assessment have been proposed in recent years, each with its own advantages and shortcomings due to particular assumptions, and many of them were basically evolved from modal updating procedures, not particularly designed for structural damage detection. A major shortcoming of the approaches based upon modal updating procedure is that the comparison of the post-damage structural modes with those of pre-damage model often requires the solution of a nonlinear programming problem which is time consuming, and may generate ambiguous results. This may bring difficulty to damage detection applications. Selecting a method as the basis to establish a damage localization criterion must account for the complexity of modal analysis and testing methods and system identification techniques while still generating physically acceptable results. Some of the practical difficulties are such as dealing with nonlinear programming, random and systematic measurement errors, selecting optimal sensor configurations, and identifying relevant modes for damage detection. The efficiency of the method also highly relies on easiness of its numerical implementation. This paper would be considerably helpful for future research, and especially beneficial for the development of a structural monitoring system in choosing an applicable and realistic method as a basis.

2. Non-Destructive Damage Detection Methods

Non-destructive damage detection is a method of detecting damage in structures or materials, without destroying the materials that constitute the structure, which is an important issue in almost all structural areas ranging from aerospace/aeronautical structures, civil infrastructures, and structural materials such as composite materials. The early detection of damage in structures is important for reasons ranging from safety to management of maintenance resources. Damage is considered as undesirable weakening of the structure which negatively affects its performance, risks the safety of a structural system. Damage may also be defined as any deviation in the structure's original geometric or materials properties which may cause undesirable stresses, displacements or vibrations on the structure. These weakness can come in the forms of cracks, reinforcement fracture, delamination, bent members, broken welds, loosen bolts or rivets, corrosion, fatigue, etc. These forms of damage may be the results of overloading and/or environmental conditions. The structural damage detection problem has evolved from the desire to reduce the risk of a catastrophic failure, to lengthen the life of the structure, to lower the maintenance cost by alleviating the current scheduled maintenance and inspection practices and inspecting only when necessary.

Aerospace/Aeronautical Structures An important technology in the design, analysis, and operation of reliable spacecraft will be the ability to remotely monitor the mechanical health of the structure. Flexible space structures, launch vehicles, rocket engines, aircraft and satellites are susceptible to structural damage over their operating lives. Structures placed in a space environment are likely to be subjected to multiple forms of damage. Damage scenarios might be impact damage inflicted by orbital debris, degradation of structural materials of some load-carrying members due to radiation and thermal cycling assembly, loosening of joints due to excessive vibration, malfunctions, faulty connections, operating loads, and fatigue. Structural damage development and resulting structural degradation of aging airframes can naturally occur as a result of the repeated takeoff/landing and pressurization/de-pressurization cycles that aircraft are routinely subjected to in the course of their duty cycles. Undetected damage in aircraft structures can lead to structural member deterioration, consequently result in mission failure, and jeopardize the flight safety including loss of life, property and financial resources. Toward this end, a variety of non-destructive evaluation techniques have been developed to detect damage in aircraft structures. A concept of self-diagnostic airplane has been proposed, that is, an airplane has the ability to detect, locate, quantify and assess the impact of precritical and larger structural damage in real-time. Developing a real-time, in-service health monitoring system for aircraft has drawn a great attention recently[2,3].

Civil Infrastructure The civil infrastructure systems, such as, highway bridges, pipelines, electrical transmission towers, etc. serve as the underpinnings of our highly industrialized society. Much of the infrastructure is now decaying because of age, deterioration, misuse, lack of repair, and in some cases, because it was not designed for current demand. The maintenance of these types of structures has, therefore, become essential to reliability. Throughout the civil infrastructure, the cost of unplanned down time caused by component failure has become compelling, but at the same time, there is ever present pressure to minimize the cost of routine maintenance and to operate the infrastructure as closely as possible to its

design limits without over stressing. In 1967, the Silver Bridge on the Ohio/West Virginia border collapsed due to an instantaneous fracture of an eyebar. As a result of this catastrophic failure, Congress required the Secretary of Transportation to establish a National Bridge Inspection Standard (NBIS), and develop a bridge inspection program. Bridge inspection standards and data reporting procedures have evolved since then to the present Bridge Management System (BMS) required by the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA)[4]. The National Science Foundation has organized several workshops on the development of structural health monitoring systems, which covered a variety of civil infrastructures such as highway/railway bridges, water/gas/petroleum pipelines, electrical transmission towers, offshore structure foundations, etc.[5]

New Advanced Materials Laminated composites such as carbon-fiber reinforced polymers are widely used in aerospace/aeronautical applications due to their high specific strength and stiffness. With good durability against corrosion, composites have also been considered for civil engineering applications. Introduction of advanced new materials and smart structures is strongly conditional on ability to assure their safety. In the course of their service life, load-carrying structural systems undergo damages including delamination, fiber fracture, penetrating defects (holes), impact damage, and matrix cracking, which should be monitored with respect to occurrence, location, and extent. Due to their inhomogeneous nature, composites exhibit much more complicated failure modes than homogeneous materials such as concrete, aluminum and steel. Among the various failure mechanisms, delamination, which is the separation of composite plies at their interface, is one of the most important failure mode for laminated composites, since delaminations affect the strength and integrity of the composite structure and may cause structural failure at a load lower than the design load. Because delaminations occur in the interior of composites, it is not detectable by surface inspections. One possible method is to use vibrational evaluation techniques to detect damages. For example, embedded optical fiber strain sensors have been used to determine the changes in vibration signature caused by delamination formation[6]; piezoelectric sensors have been used to measure the natural frequencies of composite beams before and after prescribed delaminations and therefore indicate the presence and size of the delamination[7].

The non-destructive damage detection techniques are either local (i.e. a small portion in the structure is interrogated at a time), or global (i.e. the structure is analyzed as a whole). Ideally, the damage detection process would be able to detect damage as it is incurred by the structure, determine the location and extent of the damage, predict whether and when catastrophic failure of the structure will occur, and alert the operators as to how the performance of the structure is affected so that appropriate steps can be made to remedy the situation.

Visual Inspection Visual inspection has been and still is the most common method used in detecting damage on a structure to evaluate external signs of damage such as corrosion, wear and general deterioration. Some damage scenarios may lend themselves well to visual detection, while others will be invisible, on external inspection. From these visual inspection made by trained personnel, strength determinations are usually obtained by extracting samples from the structure and testing these samples in the laboratory to determine their structural integrity, which may result in the destruction of the host structure that must be subsequently repaired to maintain the integrity of the system. These methods can be time consuming and are local assessments, often requiring the exposure of structural elements to the inspector and equipment for detecting damage. Due to the increased size and complexity of today's structures and harsh environments on which some of them are located, the efficiency of the visual inspections may be reduced. Often the structure of interest is costly and time consuming to access for conventional visual inspection, especially when disassembly is necessary to provide access to the area being inspected. In addition, these visual inspection techniques are often inadequate in identifying damage states of a structure invisible to the human eye, such as delaminations in composite materials.

Instrumental Evaluation For these reasons, numerous instrumental non-destructive evaluation techniques and monitoring procedures have been developed. Examples include X-ray radiography, ultrasonic and eddy current scanning, pulse-echo, infrared thermography, acoustic holography, magnetic resonance, coin tap, dye penetration, and stress waves method. For the most part, these methods are very well developed and widely used. Many of these approaches are passive, expensive and sometimes inconclusive. All of these non-destructive evaluation techniques are external to the structure. In addition, these are classified as local evaluation. This means that the inspections are limited to small portions of the structure. These techniques, although useful in many instances, are very expensive and involve bulky equipment, require good access to the structure, and cause a great amount of down-time for the structure. An effective inspection employing most of these technologies requires the positioning of instruments in the vicinity of the damage or defect. They are even impractical in many cases such as in-service aircraft testing, space structures, and some civil structures such as offshore structure foundations.

Vibrational-Based Assessment An alternative approach is to recognize the fact that modal vibration test data (structural natural frequencies and mode shapes) characterize the state of the structure. Assume that a refined finite element model

(FEM) of the structure has been developed before damage has occurred. By refined, we mean that the measured and analytical modal properties are in agreement. Next, assume at some later time that some form of structural damage has occurred. If significant, the damage will result in a change in the structural modal parameters. The discrepancy between the original FEM modal properties and post-damage modal properties can be used to locate and determine the extent of structural damage. Damage generally causes changes in the mechanical properties of the structural system, such as stiffness. The problem of locating a damaged site on a structure can be equated to locating regions where the stiffness or load carrying capacity has been reduced by a measurable amount. If the resonant frequencies and mode shapes are measured before and after a damage, it is possible to solve an inverse problem to determine the changes in these mechanical properties. These changes thus provide an indication of the location and magnitude of the damage. The use of vibrational assessment methods to locate structural damage has been attempted to evaluate the integrity of civil infrastructure such as highway bridges, offshore oil and gas platforms, composite laminates, continuum structures, and especially aircraft and large space structures. Modal testing as a means of inspection has several advantages. Direct exposure of structural elements is not required, and at the same time more of the complete structure can be inspected in one modal test by having appropriately placed sensors. In contrast with visual inspection and instrumental evaluation techniques which basically are local assessments, vibration-base methods rely on measurements of the global dynamic properties of structures to detect and quantify damage. The consequences of this are a reduction in schedule and cost. A variety of algorithms have been proposed that will trace differences in the two sets of data to specific or likely damaged locations.

3. Currently Available Techniques for Vibrational-Based Assessment

A number of techniques have been developed to find the changes due to damage in the vibration signature (natural frequencies, mode shapes, damping ratios). Some of these techniques include modal residual force methods[9-12], optimal matrix update method[13-28], sensitivity methods[29-34], eigenstructure assignment method[35-39], damage index method[40-43], system-identification based method[44-48], flexibility method[49], strain energy method[50-53], and intelligence-based methods[54-58], such as artificial neural network and pattern recognition. Off course, there are many other methods. A comprehensive discussion of these methods can be found in Ref.8. All these techniques have their strengths and limitations in their abilities to correctly detect, locate and quantify damage in structures using changes in vibrational characteristics. The majority of algorithms used to address the vibrational-based damage detection can be broadly classified as follows.

(1) **Modal Residual Force Method**[9-12]: which is the most straightforward method among the vibrational assessment methods for structural damage detection. Identifying the location of damage in the structure is based on differences in eigenvalues and eigenvectors of the pre-damage structure and the post-damage structure. In concept, the natural frequencies and mode shapes of the damaged structure must satisfy an eigenvalue equation. For the *ith* mode of the potentially damaged structure, the corresponding eigenvalue equation should be $\left(K_d - \lambda_{d_i} M_d\right)\phi_{d_i} = 0$, where K_d and M_d are the unknown stiffness and mass matrices associated with the damaged structure, and $\lambda_{d_i} = \omega_{d_i}^2$ is the experimentally measured eigenvalue (natural frequency squared) corresponding to the experimentally measured *ith* mode shape ϕ_{d_i} of the damaged structure. Assuming that the stiffness and mass matrices associated with the damaged structure are defined as $K_d = K_a + \Delta K$ and $M_d = M_a + \Delta M$, where K_a and M_a are the analytical refined baseline stiffness and mass matrices, and ΔK and ΔM are the unknown changes in the stiffness and mass matrices as a result of damage. Then, the eigenvalue equation for the damaged structure can be written as $\left(K_a - \lambda_{d_i} M_a\right)\phi_{d_i} = -\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i}$. The right-side term is defined as the **modal residual force** vector for the *ith* mode of the damaged structure, and designated as $R_i = -\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i}$, which is the error resulting from the substitution of the refined analytical FEM and the measured modal data into the structural eigenvalue equation. The left-side term is known, so is the modal residual force vector, and will equal to zero only if $\left(\lambda_{d_i}, \phi_{d_i}\right)$ are equal to the undamaged baseline values $\left(\lambda_{a_i}, \phi_{a_i}\right)$. Regions within the structure that are potentially damaged correspond to the degrees of freedom that have large magnitudes in R_i. Using the definition of the modal residual force vector R_i, the eigenvalue equation of the damaged structure can be written as $-\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i} = R_i$. Since the terms inside of the parentheses contain the unknown changes in stiffness and mass matrices due to damage, it is desirable to rewrite it as $[C]\{\varepsilon\} = \{Z_i\}$[16], where, $\{\varepsilon\}$ is the unknown vector of the changes in

stiffness and mass matrices containing only the terms appearing in the *j*th equation for which $R_i(j) \neq 0$. $\{Z_i\}$ is the vector consisting of the nonzero terms of R_i, and $[C]$ the coefficient matrix consisting of the measured eigenvector parameters. If the measured modes are exact, the equation then provides the exact $\{\varepsilon\}$ vector.

Ricles and Kosmatka presented a methodology for detecting structural damage in elastic structures based on modal residual force method[9]. Measured modal test data along with a correlated analytical structural model are used to locate potentially damaged regions using modal residual force vectors and to conduct a weighted sensitivity analysis to assess the extent of mass and/or stiffness variations. Sheinman developed a closed-form algorithm for precise detection using test data and likewise preserving the connectivity. This algorithm identifies the damaged degree of freedom, and then solves a set of equations to yield the damaged stiffness coefficients. Its drawback is that even a small number of damaged dof's may result in a large number of damaged stiffness coefficients with the corresponding excessive measurement volume. He then presented an algorithm which preserves the "ratio of stiffness coefficients" besides the connectivity, and thus significantly reduces the needed measurements[12].

(2) Optimal Matrix Update[13-28]: which is the largest class of FEM refinement algorithms to date. The essence of the method is to solve a closed-form equation for the matrix perturbations which minimize the modal residual force vector, or constrain the solution to satisfy it. Typically, an updating procedure seeks stiffness and/or mass correction matrices ΔK and/or ΔM such that the adjusted model $\{(K+\Delta K); (M+\Delta M)\}$ accurately predicts the measured quantities. Computing the matrix perturbations, which eliminate the modal residual force, is often an underdetermined problem, since the number of unknowns in the perturbation set can be much larger than the number of measured modes and the number of measurement degrees of freedom. In this case, the property perturbations, which satisfy the modal residual force equation, are non-unique. Thus, optimal matrix update methods apply a minimization to the property perturbation to select a solution to the residual modal force equation subject to constraints such as symmetry, positive definiteness, and sparsity. This minimization applies to either a norm or the rank of the perturbation property matrix or vector. In general, the eigenvalue equation for the damaged structure can be written as $\left(-\lambda_{d_i} M_a + j\lambda_{d_i} D_a + K_a\right)\phi_{d_i} = -\left(-\lambda_{d_i} \Delta M + j\lambda_{d_i} \Delta D + \Delta K\right)\phi_{d_i}$. The right-side term is the modal residual force vector $R_i = -\left(-\lambda_{d_i} \Delta M + j\lambda_{d_i} \Delta D + \Delta K\right)\phi_{d_i}$. The left-side term is known, and can be designated as E_i, so the eigenvalue equation can be written as $\left(-\lambda_{d_i} \Delta M + j\lambda_{d_i} \Delta D + \Delta K\right)\phi_{d_i} = E_i$, or, $[\Delta A]\phi_{d_i} = E_i$ where $[\Delta A] = \left(-\lambda_{d_i} \Delta M + j\lambda_{d_i} \Delta D + \Delta K\right)$. Conceptually, there are various optimal matrix update methods. First, *the minimum-norm perturbation* of the global matrices can be summarized as $MIN[\|[\Delta A]\|]$ subject to the constraint of the eigenvalue equation, also, the constraints of symmetry and sparsity of the matrix $[\Delta A]$. Constrainting the aparsity to be the same as the analytical FEM has the effect of ensuring that no new load paths are generated by the updated model. This approach was used by Baruch and Itzhack[16], Berman and Nagy[17], Kabe[18], and Smith and Beattie[20]. Second, *the minimum-rank perturbation* of the global matrices can be summarized as $MIN\{RANK([\Delta A])\}$ subject to the same constraints as those in the first approach. Kaouk and Zimmerman used this approach[23]. Third, *the minimum-norm, element-level update procedures* presented by Chen and Garba[10] and Li and Smith[24] incorporated the connectivity constraint between the element-level stiffness parameters and the entries in the global stiffness matrix directly into the eigenvalue equation to get $\frac{\partial}{\partial p}\left([\Delta A]\phi_{d_i}\right)\{\Delta p\} = E_i$, which is then solved for minimum-norm of $\{\Delta p\}$. Doebling provided a detailed derivation of the minimum rank elemental parameter update approach[28].

The majority of the early work in optimal matrix update used the minimum norm perturbation of the *global stiffness matrix*[16-18]. The correction matrices are usually constructed at the *global level* through the constrained minimization of a given weighted functional[17,18,25,26]. The motivation for using this objective function is that the desired perturbation is the one which is the "smallest" in overall magnitude. A common drawback of the methods is that the computed perturbations are made to stiffness matrix values at the structural DOF, rather than at the element stiffness parameter level. However, such an optimization may yield updated matrices where the symmetry and orthogonality conditions as well as the original connectivity are destroyed. Penalty techniques and Lagrangian multipliers are then often required to enforce these constraints[17,18,28], which undoubtfully increases the computational effort. Moreover, a global updating of the FEM matrices is useful only if corrections bring the understanding of what truly differs between the real structure and its modeling. With global adjustment schemes, this physical meaning is usually difficult to interpret, which

makes damage prediction hazardous. In order to keep the symmetry, positive definiteness, and connectivity properties, or keep the original load pathes uncorrupted, an *element-by-element parameter based updating method* should be considered. Once the FEM has been adjusted, changes in the physical parameters of the system are available at the element level, which greatly facilitates the understanding of modeling errors or damage locations. Computing perturbations at the elemental parameter level uses the sensitivity of the entries in the stiffness matrix to the elemental stiffness parameters so that the minimum-norm criterion can be applied directly to the vector of elemental stiffness parameters. The resulting update consists of a vector of elemental stiffness parameters that is a minimum-norm solution to the optimal update equation. There are three main advantages to computing perturbations to the elemental stiffness parameters rather than to global stiffness matrix entries: (1) The resulting updates have direct physical relevance, and thus can be more easily interpreted in terms of structural damage or errors in the FEM; (2) The connectivity of the FEM is preserved, so that the resulting updated FEM has the same load path set as the original one; and (3) A single parameter, which affects a large number of structural elements can be varied independently.

(3) Sensitivity Methods[29-34]: which make use of sensitivity derivatives of modal parameters such as modal frequencies and mode shapes with respect to physical structural design variables such as element mass and stiffness, section geometry, and material properties, to iteratively minimize the modal residual force vector[29-31]. The derivatives are then used to update the physical parameters. These algorithms result in updated models consistent within the original finite element program framework. The modal residual force vector is defined as $R_i = -\left(-\lambda_{d_i}\Delta M + \Delta K\right)\phi_{d_i} = \left(K_a - \lambda_{d_i}M_a\right)\phi_{d_i}$, where the rightmost term is known and will be equal to zero for an undamaged structure. Assume that the selected measured vibrational characteristics are contained in a vector $\Lambda^T = \left\{\omega^2, \phi\right\}^T$; the unknown structural parameters in damaged region are contained in a vector r. The subscripts "a" and "d" are used to correspond to the analytical refined structural model and damaged structural model, respectively. The relationship between these vectors can be established by using a first-order Taylor series expansion, $\Lambda_d = \Lambda_a + T\left(r_d - r_a\right) + \varepsilon$, where, ε is a vector of measurement errors associated with each measured parameter, such as natural frequencies and mode shape amplitudes. Matrix T is a *sensitivity matrix* that relates modal parameters and the physical structural design variables, $T = \begin{bmatrix} \dfrac{\partial \omega^2}{\partial K} & \dfrac{\partial \omega^2}{\partial M} \\ \dfrac{\partial \phi}{\partial K} & \dfrac{\partial \phi}{\partial M} \end{bmatrix}_a \begin{bmatrix} \dfrac{\partial K}{\partial r} \\ \dfrac{\partial M}{\partial r} \end{bmatrix}_a$. The derivatives are determined from the analytical baseline data Λ_a and r_a indicated by the subscript "a". The four individual submatrices in the first matrix of T represent partial derivatives of the eigenvalues and mode shapes with respect to the coefficients of the stiffness and mass matrices, whereas the second matrix of T represents the partial derivatives of the stiffness and mass matrices with respect to the structural parameters r. For mode k and considering measurement points i and j, it can be shown that[32],

$$\frac{\partial \omega_k^2}{\partial K_{ij}} = \frac{\phi_{ik}\phi_{jk}}{\phi_k^T M \phi_k} ; \qquad \frac{\partial \phi_{rk}}{\partial K_{ij}} = \sum_{n=1}^{q}\left[\frac{\phi_{in}\phi_{jk}\phi_{rn}}{\left(\omega_k^2 - \omega_n^2\right)\phi_n^T M \phi_n}\right]\left(1 - \delta_{nk}\right)$$

$$\frac{\partial \omega_k^2}{\partial M_{ij}} = \frac{-\omega_k^2\phi_{ik}\phi_{jk}}{\phi_k^T M \phi_k} ; \qquad \frac{\partial \phi_{rk}}{\partial M_{ij}} = \sum_{n=1}^{q}\left[\frac{-\omega_k^2\phi_{in}\phi_{jk}\phi_{rn}\left(1 - \delta_{nk}\right)}{\left(\omega_k^2 - \omega_n^2\right)\phi_n^T M \phi_n} - \frac{\phi_{in}\phi_{jk}\phi_{rn}\delta_{nk}}{2\phi_n^T M \phi_n}\right]$$

where, n is the mode number, and q is the number of retained modes in Λ_a for assessment. The goal is to determine r_d; the components of r_d include the elements in ΔK and/or ΔM in the expression of the modal residual force vector. Direct application of nonlinear optimization using sensitivity analysis to the damage detection problem has been studied by Kajela and Soeiro[33] and Soeiro[34]. In their technique, it is required that the physical design variables be chosen such that the properties of the damaged component can be varied. This presents a practical difficulty in that the number of design variables required may grow quite large, although techniques utilizing continuum approximations are discussed as one possible solution to decrease the number of design variables.

(4) Control-Based Eigenstructure Assignment Techniques[35-39]: which design a controller, known as the "*pseudo-control*", that minimizes the modal residual force vector. The controller gains are then interpreted in terms of structural parameter modifications[35]. The pseudo-control produces the measured modal properties with the initial structural model, and is then translated into matrix adjustments applied to the initial FEM[36-38]. Inman and Minas discussed two techniques for FEM refinement[36]. The first assigns both eigenvalue and eigenvector information to produce updated damping and

stiffness matrices. An unconstrained numerical nonlinear optimization problem is posed to enforce symmetry of the resulting model. A second approach, in which only eigenvalue information is used, uses a state-space formulation that finds the state matrix that has the measured eigenvalues and that is closest to the original state matrix. Zimmerman and Widengem incorporated eigenvalue and eigenvector information in the FEM using a symmetry preserving eigenstructure assignment theorem[37-38]. This algorithm replaces the unconstrained optimization approach of Ref.36 with the solution of a generalized algebraic Riccati Equation whose dimension is defined solely by the number of measured modes. Zimmerman and Kaouk extended the eigenstructure assignment algorithm of Ref.37 to approach the damage location problem better[39]. A subspace rotation algorithm is developed to enhance eigenvector assignability. Because load path preservation may be important in certain classes of damage detection, an iterative algorithm is presented that preserves the load path if the experimental data is consistent. His algorithm begins with a standard structural model with a feedback control, $M\ddot{w} + D\dot{w} + Kw = B_0 u$, where, M, D, and K are the $n \times n$ analytical mass, damping, and stiffness matrices, w is an $n \times 1$ vector of positions, B_0 is the $n \times m$ actuator influence matrix, u is the $m \times 1$ vector of control forces. In addition, the $r \times 1$ output vector y of sensor measurements is given by $y = C_0 w + C_1 \dot{w}$, where, C_0 and C_1 are the $r \times n$ output influence matrices. The control law taken is a general linear output feedback controller, $u = Fy$, where, F is the feedback gain matrix. Rearranging all the equations above, the structural system equation can be written as

$M\ddot{w} + (D - B_0 F C_1)\dot{w} + (K - B_0 F C_0)w = M\ddot{w} + D_a \dot{w} + K_a w = 0$. It's clear that the matrix triple products $B_0 F C_0$ and $B_0 F C_1$ result in changes in the stiffness and damping matrices respectively. These triple products can then be viewed as perturbation matrices to the stiffness and damping matrices such that the adjusted finite element model matches closely the experimentally measured modal properties. Consequently, the changes in the stiffness and damping matrices due to damage can be found. Unfortunately, these perturbation matrices are, in general, non-symmetric when calculated using standard eigenstructure assignment techniques, thus yielding adjusted stiffness and damping matrices that are also non-symmetric. Therefore, a symmetric eigenstructure assignment algorithm is used to determine the refined finite element model of the damaged structure. For the perturbations to be symmetric, the following conditions must be met $B_0 F C_i = C_i^T F B_0^T$, $i = 0, 1$. With the help of a generalized algebraic Ricatti Equation, matrices C_i can then be found, thereby the matrix triple products $B_0 F C_0$ and $B_0 F C_1$ can be computed. In general, the solution will not be unique, two conditions - keeping symmetry and the same definiteness of the original stiffness and damping matrices - will provide help to identify a best solution.

(5) Damage Index Method[40-43]: An important category of vibrational assessment techniques is to use a specially designed damage index to indicate the damage location and its extent. The damage index is derived based upon principles in structural dynamics. Lin suggested a type of damage index based on flexibility matrix[40]. The flexibility matrix is determined using experimental data. This matrix is then multiplied by the original stiffness matrix, with those rows and/or columns that differ significantly from a row and/or column of the identity matrix indicating which degrees of freedom have been most affected by the damage. It is then assumed that damage has occurred in structural elements connecting those degrees of freedom. Although this algorithm provides information concerning location of damage, it is difficult to determine the extent of damage. Carrasco suggested another type of damage index based on strain energy[54]. Characterizing the damage as a scalar quantity of the undamaged stiffness matrix, an expression was obtained for element damage factors that quantify the magnitude of the damage for each mode shape. This factor may take values ranging from - 1.0 to infinity, where negative values are indicative of potential damage. The most popular damage index is based on a recently developed damage localization theory attributed to Stubbs, et al[41]. This damage localization theory has been utilized to detect and localize the damages in some of civil infrastructures, such as, a real highway bridge on the US Highway I-40 located in Bernalillo County, New Mexico[42]. The criterion was also applied to the damage detection of an aerospace manipulating system and verified by a computer simulation[43]. Assume that a finite element model of the corresponding structure has been established. The damage index β_j for the jth element is given by $\beta_j = \frac{1}{2}\left[\frac{f_{ij}^*}{f_{ij}} + 1\right]$, where,

$f_{ij} = \dfrac{\int_a^b \{\phi_i^{"}(x)\}^2 dx}{\int_\Omega \{\phi_i^{"}(x)\}^2 dx}$, and $f_{ij}^* = \dfrac{\int_a^b \{\phi_i^{"*}(x)\}^2 dx}{\int_\Omega \{\phi_i^{"*}(x)\}^2 dx}$, and $\phi_i(x)$ is the pre-damage mode shape, $\phi_i^*(x)$ the post-damage mode

shape, i represents the ith mode. The domain Ω includes all elements in the structure concerned, the integration in numerator is implemented over the element i. **Damage is indicated at element j if $\beta_j > 1.0$.** To avoid possible false

indication as a damaged element is at or near a node point of the *ith* mode, the damage index β_j is commonly written as

$$\beta_j = \frac{1}{2}\left[\frac{f_{ij}^* + 1}{f_{ij} + 1} + 1\right].$$ If several modes are used in identification, say, the first M modes, then, $\beta_j = \frac{1}{2}\left[\frac{\sum_{i=1}^{M} f_{ij}^* + 1}{\sum_{i=1}^{M} f_{ij} + 1} + 1\right].$

(6) System-Identification Based Method[44-48]: System identification is the name given to the class of problems where the response of a structure is used to determine the system characteristics. There are seemingly infinite number of system identification methods that have been developed. Selecting a method of system identification for damage detection can be a significant task. One approach to the problem of damage detection is the determination of areas of reduced or zero stiffness in the structure. System identification methods that focus on the stiffness properties would then be considered for this approach. The stiffness properties for a structure are represented in various ways depending on the modeling technique. Physical parameters (such as elastic modulus in a continuous model of structure) are used in some model; while non-physical parameters (such as an element of the stiffness matrix that results from a finite element model of the structure) are identified in many other methods.

Two methods which identify non-physical parameters for discrete model are the stiffness matrix adjustment method[18] and matrix perturbation method[44]. White and Maytum's matrix perturbation method[44] uses linear perturbation of submatrices and an energy distribution analysis as the basis to determine the changes in the elements of the global stiffness and mass matrices. Kabe's method[18] used an initial estimate of the stiffness matrix, the known mass matrix, a limited set of measured modal data, and the connectivity of the structure to produce an adjusted stiffness matrix. Therefore, this method identifies nonphysical parameters, i.e. the elements of the stiffness matrix. Kabe used a so-called "scalar matrix multiplication operator $\otimes$ ", for which two matrices are multiplied, element by element, to produce a third matrix. This matrix multiplication operator provides that zero elements in the original stiffness matrix can not become non-zero elements in the final result. Each element of the adjusted stiffness matrix $[K_d]$ is the product of the corresponding elements of the original stiffness matrix $[K_a]$ and an adjustment matrix $[\gamma]$ as follows, $[K_d] = [K_a] \otimes [\gamma]$, that is, $K_{d_{ij}} = K_{a_{ij}} \gamma_{ij}$. A constrained optimization procedure is developed to minimize the percentage of each stiffness element. The error function used represents the percentage change of each stiffness matrix element, while constraints are provided from the modal analysis equations and the symmetry property of the stiffness matrix. Lagrange multipliers $[\lambda]$ are used to expand the error function to include the constraints. The resulting optimization procedure is used to solve the Lagrange multipliers. Once the Lagrange multipliers $[\lambda]$ are known, the adjusted stiffness matrix $[K_d]$ can be obtained from the original stiffness matrix $[K_a]$ and the mode shape function $[\phi]$: $[K_d] = [K_a] - \frac{1}{4}\left([K_a] \otimes [K_a]\right) \otimes \left([\lambda][\phi]^T + [\phi][\lambda]^T\right)$. Peterson et al. presented a method for detecting damage based on the comparison of mass and stiffness matrices measured prior to damage with those after the damage, rather than the comparison of respective modal parameters[45]. An advantage of this method is that the data which are compared directly indicate the presence or absence of damage. This means that no nonlinear programming problem is involved, nor is a finite element model of the structure required. The approach is based on an algorithm for transforming a state-space realization into a second-order structural model with physical displacements as the generalized coordinates. The first step is to form a state-space input-output model of the structure using a model realization procedure, such as the Eigensystem Realization Algorithm (ERA)[46]. Next, the state-space model is transformed into modal coordinates, and the mass-normalized modal vectors are determined for the output measurement set using the Common Basis Structural Identification algorithm[47]. The physical mass, damping and stiffness matrices are then synthesized by determining the Schur complement of the global coordinate model[48]. By repeating the model synthesis after damage has occured, it is possible to generate new mass and stiffness matrices of the damaged structure. An element-by-element comparison of the mass and stiffness matrices of the two models directly locates and quantifies changes in the mass and stiffness due to the damage.

(7) Flexibility Method[49]: In general, structural damage can be viewed as a reduction of stiffness. Corresponding to such a reduction in stiffness, the flexibility of a damaged member is increased. In some instances, however, additional elements are not reflected by adding additional stiffness matrix since such elements will not increase, but decrease the global stiffness of the structure. In order to account for the special problems arising from the addition of flexibility to a structure, non-destructive damage detection method using flexibility formulation has been considered. Topole's method[49] can be summarized as follows. The eigenvalue equation of a linear structural system is $\left(K - \lambda_i M\right)\phi_i = 0$. Using $A = K^{-1}$, which is the *flexibility matrix* of the structure, to substitute K, and pre-multiplying above equation with ϕ_i^T yields

$\frac{1}{\lambda_i} \phi_i^T \phi_i = \phi_i^T A M \phi_i$. For the damaged structure, the same equation holds, $\frac{1}{\lambda_{d_i}} \phi_{d_i}^T \phi_{d_i} = \phi_{d_i}^T A_d M_d \phi_{d_i}$, where, $A_d = A + \Delta A$, and $M_d = M + \Delta M$. Assume that there is no change in mass, i.e. structural damage is reflected only by changes of the flexibility matrix. Then, the above equation reduces to $\frac{1}{\lambda_{d_i}} \phi_{d_i}^T \phi_{d_i} = \phi_{d_i}^T A M \phi_{d_i} + \phi_{d_i}^T \Delta A M \phi_{d_i}$. Dividing this equation by the undamaged eigenvalue equation, and rearranging the terms results in $\frac{\phi_{d_i}^T \Delta A M \phi_{d_i}}{\phi_i^T A M \phi_i} = \frac{\lambda_i}{\lambda_{d_i}} \frac{\phi_{d_i}^T \phi_{d_i}}{\phi_i^T \phi_i} - \frac{\phi_{d_i}^T A M \phi_{d_i}}{\phi_i^T A M \phi_i}$. Defining ΔA_j as the contribution of the jth element to ΔA, and expressing ΔA_j in terms of a product of a scalar factor β_j representing the relative damage in element j, and the contribution of the jth element to the initial undamaged flexibility matrix A_j, i.e., $\Delta A_j = \beta_j A_j$, then, the above equation can be written as

$$\sum_{j=1}^{n} \frac{\phi_{d_i}^T (\beta_j A_j) M \phi_{d_i}}{\phi_i^T A M \phi_i} = \frac{\lambda_i}{\lambda_{d_i}} \frac{\phi_{d_i}^T \phi_{d_i}}{\phi_i^T \phi_i} - \frac{\phi_{d_i}^T A M \phi_{d_i}}{\phi_i^T A M \phi_i}.$$ Designating $Z_i = \frac{\lambda_i}{\lambda_{d_i}} \frac{\phi_{d_i}^T \phi_{d_i}}{\phi_i^T \phi_i} - \frac{\phi_{d_i}^T A M \phi_{d_i}}{\phi_i^T A M \phi_i}$, and $F_{ij} = \frac{\phi_{d_i}^T A_j M \phi_{d_i}}{\phi_i^T A M \phi_i}$

which can be viewed as an element of the sensitivity matrix F, describing how the ith modal parameters are affected by changes in the flexibility of the element j. A new equation, $F \cdot \beta = Z$, is then produced. Structural damage, or changes in the flexibilities of the elements, could now be determined by computing the sensitivity matrix F and the modal residual force vector Z, and then solving the set of linear equations for the unknown vector β. Note that damage is generally indicated by a reduction in stiffness which means an increase in flexibility. Thus, structural damage will be denoted by positive value of β_j.

(8) Strain Energy Method[50-53]: Strain energy distribution has been used by previous researchers as an important measure in work related to structural damage detection[10, 31, 50-53]. The investigations of these work suggest that modal data contain sufficient information to identify damage only if the damaged member's contribution of its strain energy is a significant part of the strain energy of the modes being measured. It is common therefore to assume that the identified modes which are used in the damage detection algorithm should store a large percentage of their strain energy in the members where potential damage might occur. Carrasco directly used modal strain energy for localization and quantification of damage in a space truss model[53]. The method considers the mode shapes of the structure pre- and post-damage measured via modal analysis. Values of the mode shapes at the connections are used to compute the strain energy distribution in the structural elements. Characterizing the damage as a scalar quantity of the undamaged stiffness matrix, an expression was obtained for element damage factors that quantify the magnitude of the damage for each mode shape. The total modal strain energy for the jth mode can be computed using the expression, $U_j = \frac{1}{2} \phi_j^T K \phi_j$, which can also be considered as the sum of the

strain energy in all the structural elements, $U_j = \sum_{i=1}^{n} U_{ij} = \frac{1}{2} \sum_{i=1}^{n} \phi_{ij}^T K_i \phi_{ij}$, where U_{ij} is the modal strain energy contribution

of the ith element to the jth mode. Damage brings changes in element strain energy between the undamaged and damaged structures around the vicinity of the damage. These differences can be computed by

$\Delta U_{ij} = U_{ij} - U_{d_{ij}} = \frac{1}{2} \phi_{ij}^T K_i \phi_{ij} - \frac{1}{2} \phi_{d_{ij}}^T K_{d_i} \phi_{d_{ij}}$. Assuming that the nominal undamaged properties of the element be used to approximate the damaged properties of the same element, then, a damage factor α_{ij} can be defined as

$\alpha_{ij} = \frac{U_{ij}}{U_{d_{ij}}} - 1 = \frac{\phi_{ij}^T K_i \phi_{ij}}{\phi_{d_{ij}}^T K_i \phi_{d_{ij}}} - 1$, which quantifies the damage for element i using mode j. This factor may take values

ranging from -1.0 to infinity, where negative values are indicative of potential damage.

(9) Artificial Intelligence-Based Methods[54-55]: Application of the methodology in Artificial Intelligence (AI) field to structural damage evaluation has increased significantly during the last decade[54,55]. Among others, **Pattern Recognition and Neural Network** are two popular examples. The mathematical approaches to pattern recognition may be divided into two general categories[56], namely, the syntactic (or, linguistic) approach and the decision theoretic (or, statistical) approach. The majority application of the pattern recognition method to structural failure detection and diagnostics has been the decision theoretic approach. This is a process that is generally used to digest a vast amount of data, reduce it into a

meaningful representation, and make decision on the outcome of the observation data using a classifier. Grady applied this approach to an in-flight airframe monitoring system[55]. A personal computer-based pattern recognition algorithm could be "trained" using laboratory test data, to recognize such characteristic changes in structural vibrations, and to infer from those changes the type and extent of damage in a structural component. The basic idea of neural network application is to "train" the network with known sets of structural vibration test data, and use the network to predict or identify the structural characteristics under other operating conditions. Ganguli et al have developed a neural network model to characterize the effect of damage conditions in rororcraft structure[57]. Rosario, et al applied neural technique to the damage assessment of composite structure[58]. Although neural network has many merits, it is limited to detecting only forms of damage that have been trained into the neural network. In addition, large amounts of data and time are required to train the network to learn the system model.

4. Concluding Remarks

Tools to accomplish real-time structural health monitoring are only now becoming available. The computer, with increasing data capacity and decreasing physical size and weight, has potential to collect, reduce and make decisions based on a large volume of sensor data. In addition to the traditional mechanical transducers, recent advances in the development of embedded smart sensor and actuator technology for aircraft, rocket engines, rotorcraft, and large space structures make it possible to either excite or measure structural parameters required to assess structural damage.

The use of vibrational-based nondestructive evaluation techniques to locate structural damage has been attempted to evaluate the integrity of various structures. Few researches, however, have been contributed to the application of such techniques to the rocket engine structures. It should be noted that to date most research into structural damage detection has been performed by a handful of researchers at a wide variety of sites with little or no coordination in research efforts. Many of these methods have been tested using mass-spring test models or simple planar truss models. Few of standard test problems truly embrace the essence of large flexible structures in space and as such poor judges of the performance of a few method. It would be considerably more beneficial for these methods to be tested on a more realistic model. There clearly is a gap between theoretical research and practical application. No one vibrational-based method has been successfully used in any real-world non-destructive structural damage diagnosing and monitoring system.

Finding damage when it is at an incipient level and before the global structural integrity is compromised, is most useful. One problem in previous researches, however, is that the modal analysis-based techniques are not sensitive to incipient-type damage since the techniques typically rely on lower-order global modes. The damage generally must be of a global scale for it to cause an experimentally measurable change in the lower-order global frequencies. The frequency used to interrogate the structure, i.e., excite and sense the resulting vibration magnitude and phase must much higher than those typically used in modal analysis based methods. To sense incipient-type damage which does not result in any measurable change in the structure's global stiffness properties, it is necessary for the wave length of excitation to be smaller than the characteristic length of the damage to be detected.

The other serious limitation of the modal analysis methods is the extreme sensitivity of the frequencies and modes to the boundary conditions. For aircraft structures, changes in the mass and stiffness are a part of the normal operation of aircraft, e.g., consumption of fuel from the wing fuel cells, retraction and extension of landing gears, release of external stores, movement of control surfaces and flaps, etc. Simulation of all possible normal usage changes and their effect on the modal parameters is impossible to store so as to distinguish them from damage.

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Appendix II - A Technical Paper

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Nondestructive Damage Identification
of Flexible Aerospace Manipulating Systems

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Abstract

This paper demonstrates the application of the recently developed damage localization theory to the damage identification of flexible aerospace manipulating systems. The system analyzed is a simulation of a NASA manipulator testbed for the research of the berthing operation of the Space Shuttle to the Space Station, which consists of two flexible links and three revolute joints. A finite element model using ten frame elements, along with the revolute joint element, has been developed to represent the manipulating system. Assume that one of the elements was damaged, the damage localization criterion has found the exact location of the damaged element.

Introduction

Non-destructive damage identification is a method of detecting damage in structures or materials without destroying the materials that constitute the structure, which is an important issue in aging aerospace/aeronautical structures, and civil infrastructures as well. Developing a real-time, in-service health monitoring system for aerospace/aeronau- tical structures has drawn a great attention recently[1,2]. The structural damage detection problem has evolved from the desire to reduce the risk of a catastrophic failure, to lengthen the life of the structure, to lower the maintenance cost by alleviating the current scheduled maintenance and inspection practices and inspecting only when necessary. Damage is considered as a weakening of the structure which negatively affects its performance. Damage may also be defined as any deviation in the structure's original geometric or material properties which may cause undesirable stresses, displacements or vibrations on the structure. These deviations may be due to cracks, loose bolts, broken welds, corrosion, fatigue, etc. If a structure has sustained a damage, and the damage remains undetected, the damage could progressively increase until the structure fails. Therefore, early detection, analysis, and repair of a damaged structure, if necessary, is vital for the safe performance of the structure.

86

The present method of assuring aerospace/aeronautical structural integrity is to take the structure out of service and perform inspections. During the inspection period the structure is unavailable for use. Visual inspection has been and still is the most common method used in detecting damage on a structure. Due to the increased size and complexity of today's structures and harsh environments on which some of them are located, the efficiency of the visual inspections may be reduced. Often the structure of interest is costly and time consuming to access for conventional visual inspection, especially when disassembly is necessary to provide access to the area being inspected. In addition, these visual inspection techniques are often inadequate in identifying damage status of a structure invisible to the human eye, such as delaminations in composite materials. For this reason, non-destructive evaluation techniques such as ultrasonic and eddy current scanning, acoustic emission, and X-ray inspection have been developed. These techniques, although useful in many instances, are very expensive and involve bulky equipment, require good access to the structure, and cause a great amount of down-time for the structure. They are even impractical in many cases such as in-service aerospace/aeronautical structures, and some civil structures such as offshore structure foundations. These shortcomings of current non-destructive evaluation techniques indicate the need for further development of damage identification methods which do not require direct human accessibility of the structure.

Ideally, the damage detection process would be able to detect damage as it is incurred by the structure, determine the location and extent of the damage, predict whether and when catastrophic failure of the structure will occur, and alert the operators as to how the performance of the structure is affected so that appropriate steps can be made to remedy the situation. The technique to identify damage in principle utilizes the changes in the vibration signature due to damage. As damage accumulates in a structure, the structural parameters (stiffness, mass and damping) change. The changes in structural parameters, if properly identified and classified, can be used as quantitative measures that provide the means for assessing the state of damage of the structure. Attention has focused on using changes in vibrational characteristics of structures as a means of estimating the changes in the structural parameters. The vibrational characteristics of a structure are usually extracted from conventional experimental modal analysis testing. This testing involves vibration measurements from transducers at several locations of the structure. Vibrational methods for damage assessment rely on changes in the vibrational signatures extracted from measurements taken before and after the infliction of a possible damage. The problem is always formulated as given the changes in the vibrational characteristics before and after the damage, determine the location, magnitude and the type of damage. The applications have scattered over various areas, for example, detecting damage in beam-like structures based on changes in eigenfrequencies[3,4], finding damage faults in mechanical structures[5], monitoring the integrity of offshore platforms[6] and bridges[7], and investigating the feasibility of damage detection in aerospace structures[8].

The criterion used in this paper is based on a recently developed damage localization theory attributed to Stubbs, et al[9]. This damage localization theory has been utilized to detect and localize the damages in some of civil infrastructures, such as, a real highway bridge on the US Highway I-40 located in Bernalillo County, New

Mexico[10]. The objective of this paper is to investigate the feasibility of using such theory to the damage identification of large flexible aerospace manipulating systems. The system analyzed in this paper is a simulation of a NASA manipulator testbed for the research of the berthing operation of the Space Shuttle to the Space Station[11,12]. This system consists of two flexible links and three revolute joints. A finite element model using ten frame elements, along with the revolute joint element, has been developed to represent the manipulating system. Assume that one of the elements was damaged, the damage localization criterion has found the exact location of the damaged element.

The Manipulating System

The system analyzed in this paper is a simulation of a NASA manipulator testbed for the research of the berthing operation of the Space Shuttle to the Space Station. This research testbed is planned to be the model of the berthing process constrained to move in the horizontal plane. Figure 1 illustrates the principal components of the facility. The Space Station Freedom (SSF) Mobility Base is an existing Marshall Space Flight Center (MSFC) Vehicle that has a mass of $2156.4\ kg$, referred to herein as Air Bearing Vehicle 1 (ABV1). It represents a Space Station in the berthing operation, and is considered as a payload on the end-effector. This vehicle is levitated on the MSFC flat floor facility using low flow-rate bearings. The other vehicle, the Space Shuttle (SS) Mobility Base, is attached to the wall of the flat floor facility through the shoulder joint, and will be connected to the SSF Mobility Base with a flexible two-arm manipulator system. Each arm is made of a $2.74\ m$ long aluminum I-beam with a mass of $37.089\ kg$, the flanges of which are $0.076\ m$ by $0.0032\ m$ and the web is $0.1\ m$ by $0.0032\ m$. There are three revolute joints: shoulder joint S, elbow joint E, and wrist joint W. Since the dimension of the end-effector with the payload can not be in general comparable with dimensions of the two arms, the end-effector will be abstracted as a rigid body represented by a mass point as a whole at the wrist joint. The elbow joint and wrist joint are supported by air bearings. Assume that the shoulder joint and elbow joint are driven by individual actuators independently. The control moments τ_s and τ_e are acting on the revolute joints S and E, respectively. The joint compliances are characterized by three spring constants k_x in x-direction, k_y in y-direction, and k_θ for rotation. The corresponding input joint torques are transmitted through the arm linkage to the end-effector, where the resultant force and moment act upon the Space Station Freedom Mobility Base (Air Bearing Vehicle 1 - $ABV1$).

Finite Element Model

A finite element model has been developed to represent the manipulating system. Each link is divided into five frame elements. The numbering system for finite elements and nodal points are as shown in Figure 2. The system configuration for computer simulation is assumed as follows. The up-arm has 60^0 angle with respect to the global X-axis, and the forearm has 30^0 angle. Because the two arms are not in the same orientation, it is necessary to account for the alignment of the two arms. The
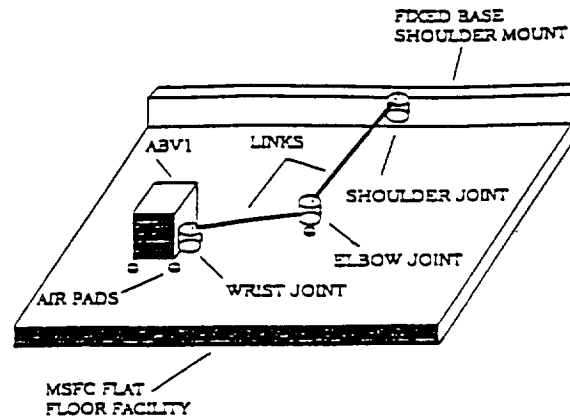
Fig.2

coordinate
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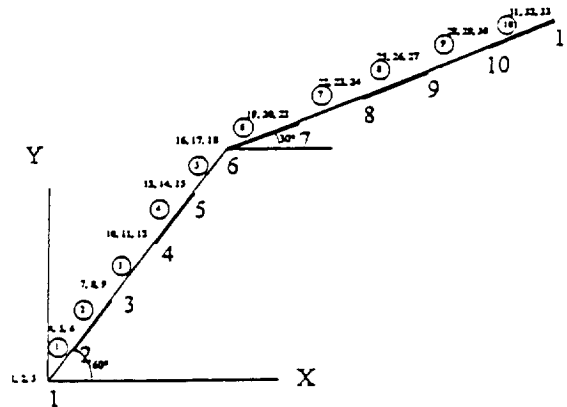Fig.1 Schematic Diagram of the NASA Manipulator Testbed

Fig.2 A Finite Element Model of A Flexible Two-Arm Manipulator System with Piezoelectric Actuators Bonded on Some of the Elements

coordinate transformation matrix between the local element coordinate system x-y and global coordinate system Z-Y can be expressed as

$$[L] = \begin{bmatrix} l & m & 0 & 0 & 0 & 0 \\ -m & l & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & l & m & 0 \\ 0 & 0 & 0 & -m & l & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where, the direction cosines are $l = cos(x,X)$, and $m = cos(x,Y)$, respectively. The element stiffness matrix in global coordinate system is then $[k]_i = [L]^T [k']_i [L]$, where $[k']_i$ is the element stiffness matrix in local coordinate system. The same transformation should also be applied to the element mass matrix. Correspondingly, the element nodal load vector in global coordinate system is $\{f\}_i = [L]^T \{f'\}_i$, where $\{f'\}_i$ is the element nodal load vector in local coordinate system. For each beam element, the nodal displacement vector consists of the axial and lateral displacements and slopes at the two nodal points, that is, $\{y\}_i = \{u_i, v_i, \theta_i, u_{i-1}, v_{i-1}, \theta_{i-1}\}^T$, and the nodal force vector consists of axial forces, shears and bending moments at the same nodal points, that is, $\{f\}_i = \{V_i, Q_i, M_i, V_{i-1}, Q_{i-1}, M_{i-1}\}^T$. The stiffness matrix $[k]_i$ and the consistent mass matrix $[m]_i$ of the ith beam element take the forms of [13]

$$[k]_i = \begin{bmatrix} \dfrac{E_i A_i}{l_i} & 0 & 0 & -\dfrac{E_i A_i}{l_i} & 0 & 0 \\ 0 & \dfrac{12 E_i I_i}{l_i^3} & \dfrac{6 E_i I_i}{l_i^2} & 0 & -\dfrac{12 E_i I_i}{l_i^3} & \dfrac{6 E_i I_i}{l_i^2} \\ 0 & \dfrac{6 E_i I_i}{l_i^2} & \dfrac{4 E_i I_i}{l_i} & 0 & -\dfrac{6 E_i I_i}{l_i^2} & \dfrac{2 E_i I_i}{l_i} \\ -\dfrac{E_i A_i}{l_i} & 0 & 0 & \dfrac{E_i A_i}{l_i} & 0 & 0 \\ 0 & -\dfrac{12 E_i I_i}{l_i^3} & -\dfrac{6 E_i I_i}{l_i^2} & 0 & \dfrac{12 E_i I_i}{l_i^3} & -\dfrac{6 E_i I_i}{l_i^2} \\ 0 & \dfrac{6 E_i I_i}{l_i^2} & \dfrac{2 E_i I_i}{l_i} & 0 & -\dfrac{6 E_i I_i}{l_i^2} & \dfrac{4 E_i I_i}{l_i} \end{bmatrix} \quad (2)$$

$$[m]_i = m_i \begin{bmatrix} \dfrac{1}{3} & 0 & 0 & \dfrac{1}{6} & 0 & 0 \\ 0 & \dfrac{13}{35} & \dfrac{11 l_i}{210} & 0 & \dfrac{9}{70} & \dfrac{13 l_i}{420} \\ 0 & \dfrac{11 l_i}{210} & \dfrac{l_i^2}{105} & 0 & \dfrac{13 l_i}{420} & -\dfrac{l_i^2}{140} \\ \dfrac{1}{6} & 0 & 0 & \dfrac{1}{3} & 0 & 0 \\ 0 & \dfrac{9}{70} & \dfrac{13 l_i}{420} & 0 & \dfrac{13}{35} & -\dfrac{11 l_i}{210} \\ 0 & -\dfrac{13 l_i}{420} & -\dfrac{l_i^2}{140} & 0 & -\dfrac{11 l_i}{210} & \dfrac{l_i^2}{105} \end{bmatrix} \quad (3)$$

where, l_i is the length of the ith beam element, $m_i = \rho A_i l_i$ its mass, $E_i I_i$ its flexural rigidity.

For aluminum material, the Young's modules $E_b = 7.6 \times 10^8 \, N/m^2$, and density $\rho = 2840 kg/m^3$. The second moment of area for the given I-beam cross-section $I_b = 0.1562 \times 10^{-3} m^4$. For convenience, an equivalent rectangular cross section with height $h = 0.0627 \, m$ and width $b = 0.076 \, m$ is used in computation, which provides the same value of the second moment of area.

Stiffness Matrix of a Revolute Joint

The function of a revolute joint is to connect two links of a kinematic assemblage. The connected links can have relative rotational motion, but the two nodes (say, I and J) on each of the connected elements respectively are actually coincident with each other (compatibility condition). For a planar manipulating system, each node has three degrees of freedom, that is, the translational motions u and v, and rotational motion θ. Since a joint consists of two nodes I and J, although they are coincident, a joint has six degrees of freedom. Assume that the translational stiffnesses are represented by translational spring constants k_x and k_y, the rotational stiffness by rotational spring constant k_θ. Based on the compatibility condition and moment equilibrium, six equations can be written in matrix form,

$$\begin{bmatrix} k_x & 0 & 0 & -k_x & 0 & 0 \\ 0 & k_y & 0 & 0 & -k_y & 0 \\ 0 & 0 & k_\theta & 0 & 0 & -k_\theta \\ -k_x & 0 & 0 & k_x & 0 & 0 \\ 0 & -k_y & 0 & 0 & k_y & 0 \\ 0 & 0 & -k_\theta & 0 & 0 & k_\theta \end{bmatrix} \begin{Bmatrix} u_I \\ v_I \\ \theta_I \\ u_J \\ v_J \\ \theta_J \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \tau \\ 0 \\ 0 \\ -\tau \end{Bmatrix} \tag{4}$$

where, the coefficient matrix $[k]_R$ is the stiffness matrix of a *Joint R*, and τ is the joint moment. Note that $[k]_R$ is singular for joint itself, that is, $Det[k]_R = 0$, but it will not bring singularity into the global system. The inertia of the joint is assumed to be neglected.

Criterion and Damage Identification

The criterion used in this paper is based on a recently developed damage localization theory attributed to Stubbs, et al. The damage index β_j for the *jth* element is given by

$$\beta_j = \frac{1}{2}\left[\frac{f_v^*}{f_v} + 1\right] \tag{5}$$

where, $f_v = \dfrac{\int_a^b \left\{\phi_i^{"}(x)\right\}^2 dx}{\int_\Omega \left\{\phi_i^{"}(x)\right\}^2 dx}$, and $f_v^* = \dfrac{\int_a^b \left\{\phi_i^{*"}(x)\right\}^2 dx}{\int_\Omega \left\{\phi_i^{*"}(x)\right\}^2 dx}$, and $\phi_i(x)$ is the pre-damage mode shape, ϕ_i^* the post-damage mode shape, i represents the *ith* mode. The domain Ω

includes all elements in the structure concerned, the integration in numerator is implemented over the element i. Damage is indicated at element j if $\beta_j > 1.0$. To avoid possible false indication as a damaged element is at or near a node point of the ith mode, the damage index β_j is commonly written as

$$\beta_j = \frac{1}{2}\left[\frac{f_j^* + 1}{f_j + 1} + 1\right] \tag{6}$$

If several modes are used in identification, say, the first M modes, then,

$$\beta_j = \frac{1}{2}\left[\frac{\sum_{i=1}^{M} f_{ij}^* + 1}{\sum_{i=1}^{M} f_{ij} + 1} + 1\right] \tag{7}$$

The pre-damage mode shape is computed after the finite element model is assembled. Assume that there is a crack reaching half of the height h of the cross section in the element 8 such that the second moment of area I is decreased to $1/8$ of the original since $I = \frac{1}{12}bh^3$. The post-damage mode shape is then computed. The first ten modes are considered in the computation. The values of these natural frequencies (in Hz) are 0.6555, 4.4265, 4.4468, 12.293, 12.294, 24.201, 24.336, 40.301, 40.540, 47.330. Based on Eq.7, the values of β_j for each of the elements are calculated and shown in the following table. It is clear that only one β-value, that is, $\beta_8 = 1.8785$, is greater than one, which indicates that element 8 is damaged.

Element	1	2	3	4	5	6	7	8	9	10
β-value	0.9407	0.9896	0.3820	0.9893	0.9405	0.7694	0.3481	*1.8785*	0.3927	0.9096

Concluding Remarks

This paper demonstrates that the recently developed damage localization theory is applicable for the damage identification of large flexible aerospace structures. The criterion has found the exact location of the damaged element in a large flexible aerospace manipulating system consisting of two flexible links and three revolute joints, modeled by a finite element model using ten frame elements, along with the revolute joint. This paper, however, is only a theoretical investigation of the feasibility. The real implementation of the procedure will depend on the measurements from both pre-damaged and post-damaged structures, from which the required mode shape information can be extracted.

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Appendix III - A Proposal for Fiscal Year 1998-1999

Shen, J.Y. and Sharpe, L., Jr., **"Development of a Structural Damage Diagnostic and Monitoring System for Rocket Engines, Phase I: Structural Modeling for Typical Engine Components"**, Submitted to NASA Lewis Research Center, December 1997.

DEVELOPMENT OF A STRUCTURAL DAMAGE DIAGNOSTIC AND MONITORING SYSTEM FOR ROCKET ENGINES
PHASE I: STRUCTURAL MODELING FOR TYPICAL ENGINE COMPONENTS

A Proposal Submitted to NASA Lewis Research Center

By

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November 1997

TABLE OF CONTENTS

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A Proposal Submitted to NASA Lewis Research Center

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Abstract

A new sub-system, functioning for non-destructive structural damage diagnosing and monitoring, has been suggested to be added and consistent with the existing NASA's generic post-test/post-flight automated diagnostic system for rocket engines. Its function is to detect damage as it is incurred by the engine structures. The sub-system consists of five sub-modules: Structural Modeling, Measurement Data Pre-Processor, Structural System Identification, Damage Detection Criterion, and Computer Visualization. The technique to identify damage in principle utilizes the changes in the vibration signature due to damage.

An intensive feasibility investigation has been conducted under NASA Grant-NAG3-2055 during the Fiscal Year of 1997. Hundreds of technical papers in the vibrational assessment area have been reviewed. A comprehensive overview of various vibrational-based non-destructive evaluation techniques is provided in this proposal. The use of vibrational-based nondestructive evaluation techniques to locate structural damage has been attempted to evaluate the integrity of civil infrastructures, such as highway bridges, offshore-oil and gas platforms, composite laminates, continuum structures, and especially aircraft and large space structures. *Few researches, however, have contributed to the application of such techniques to the rocket engine structures. There clearly is a gap between theoretical research and practical application.* No one vibrational-based method has been successfully used in any real-world non-destructive structural damage diagnosing and monitoring system.

The task to develop the entire proposed system is very heavy. With limited financial resources available, we suggest that the task for the Fiscal Year 1998 will concentrat on developing structural modeling techniques for typical engine components, which is the first step to start the entire research program. The following stages of the research will heavily rely on the accuracy of the model developed in this phase. A general finite element analysis package will be installed for general purpose of structural modeling. A data exchange program will be developed towards a certain engine structural component. In this stage, the finite element models of two typical types of structural components, which closely relate to the engine structures, will be developed: one is the blade on an engine rotor; and the other is the thin-

walled shell-type structures such as chamber wall or nozzle wall assumed as a hollow cylindrical thin-walled shell. Meanwhile computer facility will be prepared for hosting the entire system in future. The estimated total budget for the Fiscal Year 1998 is $50,000.

Introduction

NASA has initiated an effort to develop a generic post-test/post-flight diagnostic system for rocket engines. The ability to automate the functions performed by the engineers would benefit both current and future rocket engines. So far the automated diagnostic system has not functioned for detection of potential damages in the rocket engine structures. In reality, however, adding a module in the automated diagnostic system to monitor the healthy condition of rocket engine structures is a crucial task. The rigorous structural design specification, non-analytical predictable structural anomaly, and hazardous working conditions are all bringing the necessity of frequent inspections of the structural components after an engine has been flown or tested.

A new module, which functions as a non-destructive structural damage diagnosing and monitoring sub-system, has been suggested to be added and consistent with the existing NASA's automated diagnostic system. The function of this sub-system is to detect damage as it is incurred by the engine structures, determine the location and extent of the damage, predict whether and when catastrophic failure of the structure will occur, and alert the operators as to how the performance of the structure is affected so that appropriate steps can be made to remedy the situation. The technique to identify damage in principle utilizes the changes in the vibration signature due to damage. As damage accumulates in a structure, the structural parameters (stiffness, damping, and mass) change. The changes in structural parameters, if properly identified and classified, can be used as quantitative measures that provide the means for assessing the state of damage of the structure. The problem is always formulated as given the changes in the vibrational characteristics before and after the damage, determine the location, magnitude and the type of damage.

Tools to accomplish real-time structural health monitoring are only now becoming available. The computer, with increasing data capacity and decreasing physical size and weight, has potential to collect, reduce and make decisions based on a large volume of sensor data. In addition to the traditional mechanical transducers, recent advances in the development of embedded smart sensor and actuator technology for aircraft, rocket engines, rotorcraft, and large space structures may reduce the need for visual inspection to assess structural integrity and mitigate potential risk. These sensors and actuators are typically made up of a variety of materials including piezoelectric, shape memory alloy, magneto-strictive, electro-rheological and magneto-rheological fluids, and fiber optic sensors. These materials can typically be embedded into the host matrix material of the structure during manufacture, or attached externally to any structural material, to either excite or measure its parameters required to assess structural damage.

An intensive feasibility investigation has been conducted under NASA Grant-NAG3-2055 during the Fiscal Year of 1997. Hundreds of technical papers in the vibrational assessment area have been reviewed. A comprehensive overview of various vibrational-based non-

destructive evaluation techniques, which includes a brief introduction of the theoretical background of different methods, an analysis of their advantages and drawbacks, and a foresight of the applications of different methods towards different type of structures, has been provided and submitted to the International Symposium on Non-Destructive Evaluation of Aging Structures.

The use of vibrational-based nondestructive evaluation techniques to locate structural damage has been attempted to evaluate the integrity of civil infrastructures, such as highway bridges, offshore-oil and gas platforms, composite laminates, continuum structures, and especially aircraft and large space structures. *Few researches, however, have contributed to the application of such techniques to the rocket engine structures.* It should be noted that to date most research into structural damage detection has been performed by a handful of researchers at a wide variety of sites with little or no coordination in research efforts. Many of these methods have been tested using mass-spring test models or simple planar truss models. Few standard test problems truly embrace the essence of large flexible structures in space and as such poor judges of the performance of a few methods. It would be considerably more beneficial for these methods to be tested on a more realistic model. *There clearly is a gap between theoretical research and practical application.* No one vibrational-based method has been successfully used in any real-world non-destructive structural damage diagnosing and monitoring system.

A new module, functioning as a non-destructive structural damage diagnosing and monitoring sub-system, should be consistent with the existing NASA's automated diagnostic system so that the generic core of the existing system's software can be used in common, that is, the general data review functions and software system handlers will be provided by the original system, and any customized software for a particular engine can also be shared with the new module. Many automated features, such as, a plotting package, statistical routines, and frequently used engine and component models, provided by the existing system can also be referred. The same guidelines used in that system will be followed in the development of the structural module so that the two requirements will be satisfied for the new module. This new module consists of five sub-modules: Structural Modeling, Measurement Data Pre-Processor, Structural System Identification, Damage Detection Criterion, and Computer Visualization. The structural modeling module will contain two sessions: a general finite element analysis package, such as, NASTRAN, ANSYS, STAAD III, etc., and an interface to accept the structural parameters of a particular engine which is thus engine-specific. The data pre-processor module will basically complete the tasks, such as, filtering, Fast Fourier Transformation (FFT), power spectrum analysis, etc. The system identification module is programmed to extract modal properties from the experimental data. Based on those modal properties, the damage detection module then localizes the damage sites. The purpose of computer visualization module is not only for providing visual impression, but also for instantly warning and anomaly recording. For some extreme cases, the incipient-type damage would progressively expand so fast that there might not be enough time to avoid a catastrophic failure, the recorded message of structural failure stored in *"black box"* would definitely have unique value for cause analysis. As an example, if we had had this type of system installed, then, we would never have had such chaos situation after TWA Flight 800 crashed into the Atlantic Ocean!

The task to develop the entire proposed system is very heavy. With a limited financial resource available, we suggest that the task for the Fiscal Year 1998 will be concentrated on developing structural modeling sub-system for a pilot engine component, which is the first step

to start the entire research program. The following stages of the research will heavily rely on the accuracy of the model developed in this phase. A general finite element analysis package will be installed for general purpose of structural modeling. A data exchange program will be developed towards a certain engine structural component. In this stage, the finite element models of two typical types of structural components, which closely relate to the engine structures, will be developed: one is the blade on an engine rotator; and the other is the thin-walled shell-type structures such as chamber wall or nozzle wall assumed as a hollow cylindrical thin-walled shell. Meanwhile computer facility will be prepared for hosting the entire system in future. The estimated total budget for the Fiscal Year 1998 is $50,000.

1. Preclude - NASA's Initiatory Effort
to Develop a Generic Automated Diagnostic System

The Space Shuttle Main Engine (SSME) is a complex reusable rocket engine that is constantly tested and monitored in order to ensure safety and improve performance. The safe and reliable operation of a rocket engine can be increased by continuous and comprehensive monitoring of all launch vehicle data. A large engineering effort is spent analyzing post-test/post-flight sensor data to determine whether test objectives were met and whether any anomalous conditions or failures were present. This data review process is very time consuming and labor intensive. For example, the Atlas Vehicle and ground support equipment have approximately 1,500 analog and discrete measurements that are telemetered to ground receivers on two 256 Kb/sec pulse code modulated data streams. So much information is available that, during pre-flight checkout, only data which are directly related to the test underway is evaluated by system engineers. Because it is not possible to manually screen all of the pre-flight data, problems may go undetected until a redline violation on launch day or may not be observed at all. In the event of flight failure, teams of engineers pour over telemetry data searching for possible causes. Thus, data analysis tasks can be a significant percentage of overall operational costs.

The heavy reliance on knowledge of the engine system, past tests, and information access makes the data review process a labor-intensive and time-consuming task. Usually the amount of time required for reviewing the flight data is greater than that required for a test. After an engine has been flown or tested, the engineers spend a considerable amount of time determining whether an engine component, subsystem, or system operated normally. The digitized information from test firings are transferred to teams of data analysts. The data is placed in time profile plot packages and disseminated to various specialized analysis groups, including: system-level performance analysis, combustion devices, dynamics and turbomachinery. Each group reviews the plots in order to detect any anomalies in the data. Once an anomaly is discovered, hypotheses about the anomaly's cause are generated and verified by further analyzing the remaining plot information, inspecting past performance of the engine and test stand, and consulting with other specialized data analysts. The engineers receive the data in the form of various graphs, validate the data to insure proper sensor/instrumentation operation, review the data anomalous conditions, and form conclusions as to the operation of the rocket engine. The review of the data plots is an iterative procedure which involves comparing the current data to

4

past data, highlighting anomalous signatures, formulating a hypothesis as to the cause of the anomaly, and proving the hypothesis. The successful completion of the review of the data plots relies heavily on the extensive knowledge required by the engineers. The engineers must know not only general engineering principles, but also specifics about the engine operation and design, and how to access information sources. In some cases, the engineers may need additional information when investigating anomaly in the test data. In the case of an anomaly, engineers rely heavily on past experience to remember the appropriate test(s) that have had a similar anomaly. The engineers must then retrieve the appropriate sensor plot for comparison to the current test. Depending on which past tests need to be retrieved, the engineers may locate the required graphs from a computer or paper database.

The ability to automate the functions performed by the engineers would benefit both current and future rocket engines, and allow system analysts the freedom to spend more time analyzing non-routine engine behavior. An effort was initiated by NASA to develop a generic post-test/post-flight diagnostic system for rocket engines[1]. This automated system relies upon both procedural- and knowledge-based software techniques implemented using a modular architecture. The SSME is used as the first application of the generic post-flight/post-test diagnostic system. Even though the first application of this system is the SSME, the system is designed with a generic core of software that is non-engine specific. This generic core of software handles the common data review functions and software system handlers. The system also includes software which can be customized for a particular engine. The diagnostic system under development initially filters the data so that only the most critical sensor information is highlighted and presented to the engineers. The system also provides many automated features, such as, a plotting package, statistical routines, and frequently used engine and component models. These automated features are designed for ease of use, and allow the engineers to find the required analysis tools in one software package. In the future, more encompassing diagnostic techniques and prognostic capabilities will be added to the system, such as, pattern recognition techniques[2], neural networks[3], and quantitative models[4]. This will improve the current data review process, in that information as to the time for replacement of a component is based on need rather than scheduled maintenance. The near-term potential of the system is to provide the engineers reviewing flight or test data with an expedient means of reducing and interpreting the large amount of sensor data. Also, by developing and using the system, insight into the types of algorithms and processes beneficial to performing rocket engine diagnostics and prognostics will be developed. By providing a better understanding of the propulsion system and its components, and the automation necessary for the diagnostic analysis procedures, the groundwork for developing an in-flight, or real-time, diagnostic/prognostic system is being developed. Two basic requirements of the automated diagnostic system are: (1) That the system be generic, and (2) That the system automate the data review process. In order to satisfy these requirements the system was designed using the following guidelines: (1) Modular design with emphasis on non-engine specific core modules; (2) Capable of handling large amounts of data; (3) Include the types of knowledge required by the data review engineers; and (4) Interface with a variety of information sources.

2. A Crucial Task - Adding a New Module
for Monitoring Structural Healthy Condition

So far the automated diagnostic system has not functioned for detection of potential damages in rocket engine structures. In reality, however, adding a module in the automated diagnostic system to monitor the healthy condition of rocket engine structures is a crucial task. **The complexity in structures, geometry, and material composition makes it impossible to predict structural anomaly analytically.** Rocket engine is a very complex assembly consisting of a propellant/oxidizer supply and feed system, thrust chamber (a combination of a combustion chamber and an exhaust nozzle), and a cooling system. Liquid propellant stored in suitable tanks must be carried to the combustion chamber and injected into it at relatively high pressure. There are two common feed systems in use. They are the gas-pressurized feed system and the turbopump propellant feed system. For the turbopump propellant feed system, the pump is driven by a turbine, through a gear train, which in turn is driven by high-pressure gases from a gas generator. The combustion chamber must have an appropriate array of propellant injectors, and a volume in which the propellant constituents can vaporize, mix and burn; attaining near equilibrium composition before entering the nozzle. For a solid-propellant rocket, the combustion chamber is a high-pressure tank containing the solid propellant and sufficient void space to permit stable combustion. An ignition system is required for both liquid and solid propellant rockets. In an attempt to offset the thrust loss associated with over expansion, nozzle shapes other than conventional internal-flow configuration have been developed. The plug nozzle and the expansion-deflection nozzle are two examples. A suitable cooling system is required. Three basic cooling methods are commonly used. For liquid propellants, a regenerative cooling system is popular, which uses the fuel or oxidizer as a coolant flowing in tubes such as nickel tubes, or passing directly outside the chamber wall. Heat lost from the hot propellant is added to the incoming propellant. For a solid propellant, it is common to surround the nozzle walls with a mass of metal or other material which absorbs heat from the hot surface. Additional cooling may be attained by the vaporization or sublimation of material from the inner surface of the chamber wall or from the wall itself. The injection of liquids or gases through porous walls is called sweat cooling, and the intentional loss of wall material is called ablation cooling.

The geometry and material composition of each component are very complex as well. For example, many nozzles are composite structures. Near the nozzle throat, where heat transfer is most severe, the wall curvature and axial variations may significantly alter the wall temperature distribution. The wall heating rate varies considerably throughout a given nozzle, reaching a maximum near the throat. In many cases, the wall consists of a composite structure of varying thermal diffusivities, and in some cases the materials are highly anisotropic. The best material is used only in the throat region, while other materials, which may be lighter, cheaper, or easier to form, are sufficient in other regions. Consideration of such factors leads to mathematically complex analysis. In addition, certain non-analytic phenomena, such as surface erosion or chemical reaction, may be of great importance. Further complications arise. **The rigorous structural design specification makes possibilities to overstress the rocket engine structures.** The performance of the rocket vehicle depends heavily on the mass of the engine. The total mass of the rocket vehicle consists of the mass of the payload, the propellant

mass and the structural mass which includes the engine, guidance and control equipment, as well as tankage and supporting structures. Large payload ratio is desirable in general, especially for the research missions which require rocket transportation of instrument payloads. For a given mass of propellant carried and a given mass ratio, every decrease in the structural mass permits an increase of equal magnitude in the payload. Thus, it is advantageous to reduce the structural coefficient, that is, to design a very light tank and support structure. Reports showed that total structural mass is only 6% of the total initial mass in designing rockets[5]. To achieve the desired light weight, design stresses are commonly much higher than those encountered in conventional earthbound structures. Stress levels in excess of 200,000 psi are common for high-strength steel-alloy structural components. Some of the lighter-alloy such as titanium-alloy structural components have withstood stress levels as high as 260,000 psi. This puts a very strict demand on the structural strength design of the vehicle.

There are a lot of possibilities to overstress the rocket engine structures. The propellant mass is much larger than the payload. The mass of the propellant tanks and support structure may be larger than the payload. Much energy is consumed in the acceleration of the structure and tankage, less is available for acceleration of the payload. In order to reduce the energy consumed in simply lifting the propellant, it is desirable to reduce the burning time as much as possible while accelerating the vehicle against a gravity field. However, very short burning time implies a very high acceleration, which may impose severe stresses on the structures.

Combustion pressure is another important fact influencing the overall vehicle performance. With the increase of the combustion pressure, thrust chamber, hence rocket size may be decreased for a given thrust. Offsetting this advantage is the increase of the thrust-chamber stresses. To alleviate the high-level stress, a relatively thick chamber wall may be used, but an increase in wall thickness will intensify the wall temperature problem. In addition, when the chamber pressure is lower than lower pressure limit or above the upper pressure limit, the combustion becomes erratic and unpredictable. The non-uniform burn-through may reduce the chamber pressure enough to extinguish the combustion before all of the propellants are consumed. Even if the combustion did not cease, the prematurely exposed chamber wall could fail due to overheating.

The hazardous working condition threatens the safety of the engine structures. Extremely high temperature brings difficulty in the design of rocket engine structures, and threatens the safety of the engine structures. For example, combustion temperatures of rocket propellants typically are higher than the melting points of common metals and alloys, and even of some refractory materials. Also, the strength of most materials declines rapidly at high temperature. For practical rockets, it is necessary to use high-temperature materials and/or special cooling effects, that is, greater solid conductivity and heat capacity. Using a certain type of cooling system such as regenerative cooling system is required. Even if a cooling system has been furnished, it is still necessary to make sure that the coolant temperature is below the local boiling temperature. Although local surface boiling might be permissible, overall boiling of the fluid is usually accompanied by rapid burnout of the chamber wall.

In sum, the rigorous structural design specification, non-analytical predictable structural anomaly, and hazardous working conditions are all factors that make it necessary for frequent inspections of the structural components after an engine has been flown or tested.

3. Necessity of Structural Health Monitoring Systems Based on Nondestructive Damage Detection Techniques

Nondestructive damage detection is an important issue in almost all structural areas ranging from aerospace/aeronautical structures, civil infrastructures, and structural materials such as composite materials. The early detection of damage in structures is important for reasons ranging from safety to management of maintenance resources. In order to maintain the performance and safe operation of structural systems, structural integrity must be monitored periodically. Damage is considered as undesirable weakening of the structure which negatively affects its performance, and risks the safety of a structural system. Damage may also be defined as any deviation in the structure's original geometric or materials properties which may cause undesirable stresses, displacements or vibrations on the structure. These weaknesses can come in the forms of cracks, reinforcement fracture, delamination, bent members, broken welds, loosen bolts or rivets, corrosion, fatigue, etc. These forms of damage may be the results of overloading and/or environmental conditions. If a structure has sustained a damage, and the damage remains undetected, the damage could progressively increase until the structure fails. Therefore. early detection, analysis, and repair of a damaged structure, if necessary, is vital for the safe performance of the structure. The structural damage detection problem has evolved from the desire to reduce the risk of a catastrophic failure, to lengthen the life of the structure, to lower the maintenance cost by alleviating the current scheduled maintenance and inspection practices and inspecting only when necessary.

Aerospace/Aeronautical Structures An important technology in the design, analysis, and operation of reliable spacecraft will be the ability to remotely monitor the mechanical health of the structure. Flexible space structures, launch vehicles, rocket engines, aircraft and satellites are susceptible to structural damage over their operating lives. Structures placed in a space environment are likely to be subjected to multiple forms of damage. Damage scenarios might impact damage inflicted by orbital debris, degradation of structural materials of some load-carrying members due to radiation and thermal cycling assembly, loosening of joints due to excessive vibration, malfunctions, faulty connections, operating loads, and fatigue. Due to the large size and complexity of envisioned structures, the use of advanced materials to reduce structural weight, as well as the costs associated with placing these structures in space, it may become necessary to develop a structural health monitoring system to detect and locate structural damage as it occurs.

Structural damage development and resulting structural degradation of aging airframes can naturally occur as a result of the repeated takeoff/landing and pressurization/de-pressurization cycles that aircraft are routinely subjected to in the course of their duty cycles. A progressive development of damage in aircraft structures can eventually lead to structural failure. If the initiation and development of this damage could be tracked nondestructively, the structure could be repaired or replaced prior to failure. Undetected damage in aircraft structures can lead to structural member deterioration, consequently result in mission failure, and jeopardize the flight safety including loss of life, property and financial resources. Toward this end, a variety of non-destructive evaluation techniques have been developed to detect damage in aircraft structures. A concept of self-diagnostic airplane has been proposed, that is, an airplane has the ability to detect. locate. quantify and assess the impact of precritical and larger structural

damage in real-time. Developing a real-time, in-service health monitoring system for aircraft has drawn great attention recently. For example, the US Air Force and US Navy have spent millions of dollars on the development of aircraft structural health monitoring systems[6,7].

Accuracy control is another concern for aerospace/aeronautical structures. A certain degree of structural redundancy has been provided in order to prevent the overall failure of a space structure if one or several of its structural members are damaged. However, even a highly redundant structure will see its dynamic behavior altered, if mass, stiffness, or damping characteristics of particular members are deteriorated. High precision requirements in maneuvers such as precise pointing in space require superior accuracy in the control and positioning laws, and therefore in the knowledge of the structure. The capability of detecting structural changes or damage induced by the space environment and measuring the actual mechanics of the structure after reconfiguration on orbit would also provide control systems or adaptive structural components with necessary information to correct or improve mission performance.

Civil Infrastructure The civil infrastructure systems, such as, highway bridges, pipelines, electrical transmission towers, etc. serve as the underpinnings of our highly industrialized society. Let us look at highway bridges only as an example. Currently, there are approximately 578,000 bridges; the total length of bridges is 13,700 miles. Much of the infrastructure is now decaying because of age, deterioration, misuse, lack of repair, and in some cases, because it was not designed for current demand. The maintenance of these types of structures has, therefore, become essential to reliability. Throughout the civil infrastructure, the cost of unplanned down time caused by component failure has become compelling, but at the same time, there is ever present pressure to minimize the cost of routine maintenance and to operate the infrastructure as closely as possible to its design limits without over stressing. Changing in use and the need to maintain an aging system require improvements in instrumentation and data monitoring for sensing the possible damage, for detecting the change in structural characteristics, and for preventing potential catastrophic events. In 1967, the Silver Bridge on the Ohio/West Virginia border collapsed due to an instantaneous fracture of an eyebar. As a result of this catastrophic failure, Congress required the Secretary of Transportation to establish a National Bridge Inspection Standard (NBIS), and develop a bridge inspection program. Bridge inspection standards and data reporting procedures have evolved since then to the present Bridge Management System (BMS) required by the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA)[8]. The National Science Foundation has organized several workshops on the development of structural health monitoring systems, which covered a variety of civil infrastructures such as highway/railway bridges, water/gas/petroleum pipelines, electrical transmission towers, offshore structure foundations, etc.[9]

New Advanced Materials Laminated composites such as carbon-fiber reinforced polymers are widely used in aerospace/aeronautical applications due to their high specific strength and stiffness. With good durability against corrosion, composites have also been considered for civil engineering applications. Introduction of advanced new materials and smart structures is strongly conditional on ability to assure their safety. In the course of their service life, load-carrying structural systems undergo damages including delamination, fiber fracture, penetrating defects (holes), impact damage, and matrix cracking, which should be monitored with respect to occurrence, location, and extent. Due to their inhomogeneous nature, composites exhibit much more complicated failure modes than homogeneous materials such as concrete, aluminum, and

steel. Among the various failure mechanisms, delamination, which is the separation of composite plies at their interface, is one of the most important failure modes for laminated composites, since delaminations affect the strength and integrity of the composite structure and may cause structural failure at a load lower than the design load. Because delaminations occur in the interior of composites, it is not detectable by surface inspections. One possible method is to use vibrational evaluation techniques to detect damages, for example, embedded optical fiber strain sensors have been used to determine the changes in vibration signature caused by delamination formation[10]; piezoelectric sensors have been used to measure the natural frequencies of composite beams before and after prescribed delaminations and therefore indicate the presence and size of the delamination[11].

4. Non-Destructive Damage Detection Methods

Non-destructive damage detection is a method of detecting damage in structures or materials, without destroying the materials that constitute the structure. The techniques are either local (i.e. a small portion in the structure is interrogated at a time), or global (i.e. the structure is analyzed as a whole). Ideally, the damage detection process would be able to detect damage as it is incurred by the structure, determine the location and extent of the damage, predict whether and when catastrophic failure of the structure will occur, and alert the operators as to how the performance of the structure is affected so that appropriate steps can be made to remedy the situation.

Visual Inspection Visual inspection has been and still is the most common method used in detecting damage on a structure to evaluate external signs of damage such as corrosion, wear and general deterioration. Some damage scenarios may lend themselves well to visual detection, while others will be invisible, on external inspection. From these visual inspections made by trained personnel, strength determinations are usually obtained by extracting samples from the structure and testing these samples in the laboratory to determine their structural integrity, which may result in the destruction of the host structure that must be subsequently repaired to maintain the integrity of the system. These methods can be time consuming and are local assessments, often requiring the exposure of structural elements to the inspector and equipment for detecting damage. For example, the present method of assuring aircraft structural integrity is to take the aircraft out of service and perform inspections. During the inspection period the aircraft is unavailable for use. Due to the increased size and complexity of today's structures and harsh environments on which some of them are located, the efficiency of the visual inspections may be reduced. Often the structure of interest is costly and time consuming to access for conventional visual inspection, especially when disassembly is necessary to provide access to the area being inspected. In addition, these visual inspection techniques are often inadequate in identifying damage states of a structure invisible to the human eye, such as delaminations in composite materials. As a monitoring system for detecting damage of spacecraft in orbit, i.e., Space Station, none of these methods are appropriate.

Instrumental Evaluation For these reasons, numerous instrumental non-destructive evaluation techniques and monitoring procedures have been developed. Examples include X-ray radiography, ultrasonic and eddy current scanning, pulse-echo, infrared thermography, acoustic

holography, magnetic resonance, coin tap, dye penetration, and stress waves method. For the most part, these methods are very well developed and widely used. Many of these approaches are passive, expensive and sometimes inconclusive. All of these non-destructive evaluation techniques are external to the structure. In addition, these are classified as local evaluation. This means that the inspections are limited to small portions of the structure. These techniques, although useful in many instances, are very expensive and involve bulky equipment, require good access to the structure, and cause a great amount of down-time for the structure. An effective inspection employing most of these technologies requires the positioning of instruments in the vicinity of the damage or defect. They are even impractical in many cases such as in-service aircraft testing, space structures, and some civil structures such as offshore structure foundations. These shortcomings of current non-destructive evaluation techniques indicate the need for damage identification methods which do not require direct human accessibility of the structure.

Vibrational-Based Assessment An alternative approach is to recognize the fact that modal vibration test data (structural natural frequencies and mode shapes) characterize the state of the structure. Assume that a refined finite element model (FEM) of the structure has been developed before damage has occurred. By refined, we mean that the measured and analytical modal properties are in agreement. Next, assume at some later time that some form of structural damage has occurred. If significant, the damage will result in a change in the structural modal parameters. The question is: Can the discrepancy between the original FEM modal properties and post-damage modal properties be used to locate and determine the extent of structural damage? The answer is *yes*. Damage generally causes changes in the mechanical properties of the structural system, such as stiffness. The problem of locating a damaged site on a structure can be equated to locating regions where the stiffness or load carrying capacity has been reduced by a measurable amount. Since the vibration characteristics of structures are functions of these properties, then damage is accompanied by changes in these characteristics. Thus, in principle, if the resonant frequencies and mode shapes are measured before and after a damage, it is possible to solve an inverse problem to determine the changes in these mechanical properties (element stiffness and masses). These changes thus provide an indication of the location and magnitude of the damage.

The use of vibrational assessment methods to locate structural damage has been attempted to evaluate the integrity of civil infrastructure such as highway bridges, offshore oil and gas platforms, composite laminates, continuum structures, and especially aircraft and large space structures. For example, for aerospace/aeronautical structures, postflight and in-flight (e.g., monitoring) data can be used to distinguish whether changes (damages) have occurred to the structure by comparing these data with a set of baseline data. Modal testing as a means of inspection has several advantages. Direct exposure of structural elements is not required, and at the same time more of the complete structure can be inspected in one modal test by having appropriately placed sensors. In contrast with visual inspection and instrumental evaluation techniques which basically are local assessments, vibration-base methods rely on measurements of the global dynamic properties of structures to detect and quantify damage. The consequences of this are a reduction in schedule and cost. The damaged regions might be identified by performing an on-orbit modal test using the spacecraft reaction control system to excite the structure and produce modal response characteristics such as frequencies and mode shapes. These parameters are used compared ...

have been proposed that will trace differences in the two sets of data to specific or likely damaged locations. The problem is complicated significantly off course by the test environment when the test is performed on orbit.

Tools to accomplish real-time structural health monitoring are only now becoming available. The computer, with increasing data capacity and decreasing physical size and weight, has potential to collect, reduce and make decisions based on a large volume of sensor data. Instead of the traditional mechanical transducers, recent advances in the development of embedded smart sensor and actuator technology for aircraft, rotorcraft, and large space structures may reduce the need for visual inspection to assess structural integrity and mitigate potential risk. These sensors and actuators are typically made up of a variety of materials including piezoelectric, shape memory alloy, magneto-strictive, electro-rheological and magneto-rheological fluids, and fiber optic sensors. These materials can typically be embedded into the host matrix material of the structure during manufacture, or attached externally to any structural material, to either excite or measure its parameters required to assess structural damage. To measure the structural dynamic properties if modal testing is conducted on ground, some advanced non-contact methods such as laser velocimetry can also be used.

It should be noted that *few researches have contributed to the application of such techniques to the rocket engine structures.* To date most research into structural damage detection has been performed by a handful of researchers at a wide variety of sites with little or no coordination in research efforts. Many of these methods have been tested using mass-spring test models or simple planar truss models. Few standard test problems truly embrace the essence of large flexible structures in space and as such poor judges of the performance of a few methods. It would be considerably more beneficial for these methods to be tested on a more realistic model. *There clearly is a gap between theoretical research and practical application.* No one vibrational-based method has been successfully used in any real-world non-destructive structural damage diagnosing and monitoring system.

One problem in previous researches is that the modal analysis-based techniques are not sensitive to incipient-type damage since the techniques typically rely on lower-order global modes. The damage generally must be of a global scale for it to cause an experimentally measurable change in the lower-order global frequencies. The frequency used to interrogate the structure, i.e., excite and sense the resulting vibration magnitude and phase must be much higher than those typically used in modal analysis based methods. To sense incipient-type damage which does not result in any measurable change in the structure's global stiffness properties, it is necessary for the wave length of excitation to be smaller than the characteristic length of the damage to be detected. Finding damage when it is at an incipient level and before the global structural integrity is compromised, is most useful. This is because it can provide us with a warning before actual failure occurs. The other serious limitation of the modal analysis methods is the extreme sensitivity of the frequencies and modes to the boundary conditions. For aircraft structures, changes in the mass and stiffness are a part of the normal operation, e.g., consumption of fuel from the wing fuel cells, retraction and extension of landing gears, release of external stores, movement of control surfaces and flaps, etc. Simulation of all possible normal usage changes and their effect on the modal parameters is impossible to store so as to distinguish them from damage. Even under very controlled conditions, it would be extremely difficult to reproduce the aircraft for modal testing in the same configuration in which the

frequency excitation, typically in the high kHz range, to the structure being monitored. At such high frequencies, the response is dominated by local modes and incipient damage like small cracks, loose connections, and delaminations, produce measurable changes in the vibration signature. The high frequencies also limit the actuation/sensing area, which helps to isolate the effect of damage on the signature from other far-field changes in mass-loading, stiffness and boundary conditions. This will be most useful in identifying and tracking damage in those areas of structures where high structural integrity must be assured at all times, for example, the main wing-fuselage joint; the engine-to-fuselage connections and other connections. This will be ideal for areas which, over the service life of the aircraft, have been identified to be weak, and as yet are difficult to inspect.

5. Currently Available Techniques for Vibrational-Based Assessment

The technique to identify damage by vibrational-based assessment in principle utilizes the changes due to damage in the vibration signature (natural frequencies, mode shapes, damping ratios). The problem is always formulated as given the changes in the vibrational characteristics before and after the damage, determine the location, magnitude and the type of damage. As damage accumulates in a structure, the structural parameters (stiffness, mass and damping) change. The changes in structural parameters which correspondingly result in changes in structural dynamic signature, if properly identified and classified, can be used as quantitative measures that provide the means for assessing the state of damage of the structure.

The vibrational characteristics of a structure are usually extracted from conventional experimental modal testing. This testing involves vibration measurements from transducers at selected locations of the structure. Methods to extract vibrational characteristics of structures fall within the subject of modal analysis. These methods rely on experimental determination of frequency response functions between an excitation input and output responses. The excitation input is usually caused with electro-mechanical shakers and the responses measured with accelerometers. For the most part, these techniques only provide quantitative measurements of resonant frequencies and qualitative measurements of the mode shapes. Since all structures are continuous systems, and since the structures are usually sampled using few accelerometers, mode shape measurements are incomplete in general.

Different types of damage result in different measurable changes in the vibrational characteristics for a wide variety of structures. For some cases, the most significant change in the vibrational characteristics due to damage is that on natural frequencies. Despite the fact that changes in the mode shapes do occur and that some of the changes can be measured, the insignificant changes in the determination of the mode shapes has prevented their use for damage detection applications. For this reason, a number of damage detection theories that have received attention are those based on frequency shifts or changes in the natural frequencies. For other cases, the differences in the natural frequencies can be very small, and this information, by itself, is not in general sufficient to detect or locate the damage. In contrast, mode shapes can be drastically affected by different damage cases, and therefore may contain more useful information for determining damage location than the frequencies alone. However, the lack of accuracy in determination of mode shapes might bring some difficulties in applications of some

damage detection methods solely based on mode shape information. Besides the frequencies and mode shapes, the kinetic and strain energies for each mode also contain important information that will help in locating damage.

A number of techniques have been developed to find these changes. Some of these techniques include residual modal force methods[13-16], optimal matrix update method[17-32], modal sensitivity methods[33-38], eigenstructure assignment method[39-43], damage index method[44-47], system-identification based method[48-52], flexibility method[53], strain distribution method[54], strain energy method[55-58], and intelligence-based methods[59-63], such as artificial neural network and pattern recognition. Off course, there are many other methods, for example, continuum-based method, which provides valuable insight into the magnitude of frequency shifts, but their usefulness is severely limited to simple structures (bars, beams, plates) with unrealistic boundary conditions. Stubbs studied damage detection in large space structures by treating the three-dimensional space truss as an equivalent Euler-Bernoulli beam. This simplistic approach accounted for changes to both mass and stiffness, but ignored the sensitivity of the mode shapes to damage. A comprehensive discussion of these methods can be found in Ref.12. All these techniques have their strengths and limitations in their abilities to correctly detect, locate and quantify damage in structures using changes in vibrational characteristics. In addition, the requirements of each different technique are different, for example, some require the extraction of modal responses over a wide frequency band; while other methods only require the measurement of a few resonant frequencies and mode shapes. Some methods also require the measurement of complete mode shapes; while others utilize realization of the modes at a few points. A lot of approaches are severely limited with the assumption that the system mass is constant and changes in vibration characteristics are associated with only stiffness variations. This might be unrealistic for large flexible space structure, where frequency shifts can be expected to occur as a result of mass variations associated with the movement of antenna, astronauts, and solar arrays; ducking of visiting spacecraft; or changing levels in fluid containers. Therefore, some methods account for changes to both mass and stiffness.

Before conducting damage assessment, a refined baseline finite element model of the original structure must be developed, considering the modeling error, fabrication-induced errors, uncertainty in the structural parameters, and instrumentation errors. Modification of a structural finite element model such that the FEM eigensolution matches the results of a modal vibration experiment is called model refinement, or model update technique, or in more general terms, system identification. The motivation behind the development of FEM refinement techniques is based on the need to "validate" analytical FEM before its acceptance as the basis for final design analysis. Performing the first-stage modal testing on a structure will correlate and calibrate the structure's analytical model in order that mode shapes and frequencies of the model and test results agree over selected frequency ranges. The resulting model contains a more accurate representation of the dynamics of the real structure. A vast amount of work has been done in this area. But, in order to use system identification in damage detection, more strict formulation must be provided, for example, maintaining element connectivity and sparsity, preservation of symmetry and positive definiteness.

After the first-stage modal updating, i.e., setting up the baseline model, the refined finite element model is considered as the accurate representative of the original undamaged structure. Any further changes in vibrational signature at some later time will be considered as the damage-induced discrepancy. The damaged model, along with the updated finite element

14

model, will be used in the damage localization process. This process searches for the structural property matrices such as stiffness and mass matrices that maintain the zero-non-zero pattern of the updated matrices, and thus do not introduce unrealistic load paths, while reproducing the modes observed during the test. This is almost a repetition of the first-stage system identification process except that instead of updating the analytical model with the new information, the process seeks out the elements of the stiffness matrix and/or mass matrix that change the most in order to produce the observed results. Once these matrix elements have been identified, a physical map of the geometry can be used to determine which elements of the structure are most likely contributors to the changes due to damage. The majority of algorithms used to address the FEM refinement and/or damage detection can be broadly classified as follows.

(1) Residual Modal Force Method[13-16]: which is the most straightforward method among the vibrational assessment methods for structural damage detection. Identifying the location of damage in the structure is based on differences in eigenvalues of the pre-damage structure (represented by a refined finite element model) and the post-damage structure. In concept, the natural frequencies and mode shapes of the damaged structure must satisfy an eigenvalue equation. For the *ith* mode of the potentially damaged structure, the corresponding eigenvalue equation should be $\left(K_d - \lambda_{d_i} M_d\right)\phi_{d_i} = 0$, where K_d and M_d are the unknown stiffness and mass matrices associated with the damaged structure, and $\lambda_{d_i} = \omega_{d_i}^2$ is the experimentally measured eigenvalue (natural frequency squared) corresponding to the experimentally measured *ith* mode shape ϕ_{d_i} of the damaged structure. Assuming that the stiffness and mass matrices associated with the damaged structure are defined as $K_d = K_a + \Delta K$ and $M_d = M_a + \Delta M$, where K_a and M_a are the analytical refined baseline stiffness and mass matrices, and ΔK and ΔM are the unknown changes in the stiffness and mass matrices as a result of damage. Then, the eigenvalue equation for the damaged structure can be written as $\left(K_a - \lambda_{d_i} M_a\right)\phi_{d_i} = -\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i}$. The right-side term is defined as the **modal residual force vector** for the *ith* mode of the damaged structure, and designated as $R_i = -\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i}$, which is the error resulting from the substitution of the refined analytical FEM and the measured modal data into the structural eigenvalue equation. The left-side term is known, so is the modal residual force vector, and will equal to zero only if $\left(\lambda_{d_i}, \phi_{d_i}\right)$ are equal to the undamaged baseline values $\left(\lambda_{a_i}, \phi_{a_i}\right)$. Regions within the structure that are potentially damaged correspond to the degrees of freedom that have large magnitudes in R_i. Using the definition of the modal residual force vector R_i, the eigenvalue equation of the damaged structure can be written as $-\left(\Delta K - \lambda_{d_i} \Delta M\right)\phi_{d_i} = R_i$. Since the terms inside of the parentheses contain the unknown changes in stiffness and mass matrices due to damage, it is desirable to rewrite it as $[C]\{\varepsilon\} = \{Z_i\}$ [16], where, $\{\varepsilon\}$ is the unknown vector of the changes in stiffness and mass matrices containing only the terms appearing in the *jth* equation for which $R_i(j) \neq 0$. $\{Z_i\}$ is the vector consisting of the nonzero terms of R_i, and $[C]$ the coefficient matrix consisting of the measured eigenvector parameters. If the measured modes are exact, the equation then provides the exact $\{\varepsilon\}$ vector. However, the number of measured modes which

are needed for solving this equation is increasing with the number of dof's of the ends of the damaged zone.

It should be emphasized that the analytical baseline finite element model must well correlate to the initial undamaged structure, otherwise, these initial errors will incorrectly dominate the estimated damage. Towards this end, one should choose those modes in the damage detection algorithm, for which the natural frequencies of the analytical baseline finite element model well correlate to those of the initial undamaged structure. So called "Modal Assurance Criterion" (MAC) and "Cross Orthogonality Check" should be applied in the selection of which experimental natural frequencies and mode shapes are to be used[13]. In addition, one should calculate the modal residual force R_i using many different modes because if a damaged member is located near a node line, then the modal displacement is near zero and the modal residual force will also be near zero. A damage detection procedure is efficient only when the identified modal set used contains information that allows to "observe" the damage. When the load-carrying capability of the structure is investigated, the quantity of information contained within the modal set can be understood in terms of strain energy. A member with higher strain energy in a certain modal set stores a fair amount of energy for this particular modal set, and is said to be "observable", that is, the member carries a non-negligible share of the overall loading, and therefore any modification of its material and/or geometrical properties affects the overall dynamics of the structure. The "observability" criterion implies that an experiment (sensor and actuator placement, choice of the excitation signal, etc.) should always be designed in order to identify those modes that contain information with respect to damage.

Ricles and Kosmatka presented a methodology for detecting structural damage in elastic structures based on residual modal force method[13]. Measured modal test data along with a correlated analytical structural model are used to locate potentially damaged regions using residual modal force vectors and to conduct a weighted sensitivity analysis to assess the extent of mass and/or stiffness variations. The approach accounted for the variations in system mass, stiffness, and mass center location; and perturbations of both the natural frequencies and mode shapes; statistical confidence factors for the structural parameters and potential experimental instrumentation error. Sheinman developed a closed-form algorithm for precise detection using test data and likewise preserving the connectivity. This algorithm identifies the damaged degree of freedom, and then solves a set of equations to yield the damaged stiffness coefficients. Its drawback is that even a small number of damaged dof's may result in a large number of damaged stiffness coefficients with the corresponding excessive measurement volume. He then presented an algorithm which preserves the "ratio of stiffness coefficients" besides the connectivity, and thus significantly reduces the needed measurements[16]. The algorithm identifies the damaged members through very few measured modes, and is suitable for large structures with thousands of dof's.

(2) Optimal Matrix Update[17-32]**:** which is arguably the largest class of FEM refinement algorithms to date. The essence of the method is to solve a closed-form equation for the matrix perturbations which minimize the residual modal force vector, or constrain the solution to satisfy it. Typically, an updating procedure seeks stiffness and/or mass correction matrices ΔK and/or ΔM such that the adjusted model $\{(K+\Delta K); (M+\Delta M)\}$ accurately predicts the measured quantities. Computing the matrix perturbations, which eliminate the residual modal force, is often an underdetermined problem, since the number of unknowns in the perturbation set can be

much larger than the number of measured modes and the number of measurement degrees of freedom. In this case, the property perturbations, which satisfy the residual modal force equation, are non-unique. Thus, optimal matrix update methods apply a minimization to the property perturbation to select a solution to the residual modal force equation subject to constraints such as symmetry, positive definiteness, and sparsity. This minimization applies to either a norm or the rank of the perturbation property matrix or vector. In general, the eigenvalue equation for the damaged structure can be written as $\left(-\lambda_{d_i} M_a + j\lambda_{d_i} D_a + K_a\right)\phi_{d_i} = -\left(-\lambda_{d_i}\Delta M + j\lambda_{d_i}\Delta D + \Delta K\right)\phi_{d_i}$. The right-side term is the residual modal force vector $R_i = -\left(-\lambda_{d_i}\Delta M + j\lambda_{d_i}\Delta D + \Delta K\right)\phi_{d_i}$. The left-side term is known, and can be designated as E_i, so the eigenvalue equation can be written as $\left(-\lambda_{d_i}\Delta M + j\lambda_{d_i}\Delta D + \Delta K\right)\phi_{d_i} = E_i$, or, $[\Delta A]\phi_{d_i} = E_i$

where $[\Delta A] = \left(-\lambda_{d_i}\Delta M + j\lambda_{d_i}\Delta D + \Delta K\right)$. Conceptually, various optimal matrix update methods can be described as follows. First, *the minimum-norm perturbation* of the global matrices can be summarized as $MIN\|[\Delta A]\|$ subject to the constraint of the eigenvalue equation, also, the constraints of symmetry and sparsity of the matrix $[\Delta A]$. Constrainting the aparsity to be the same as the analytical FEM has the effect of ensuring that no new load paths are generated by the updated model. This approach was used by Baruch and Itzhack[20], Berman and Nagy[21], Kabe[22], and Smith and Beattie[24]. Second, *the minimum-rank perturbation* of the global matrices can be summarized as $MIN\{RANK([\Delta A])\}$ subject to the same constraints as those in the first approach. Kaouk and Zimmerman used this approach[27]. Third, *the minimum-norm, element-level update procedures* presented by Chen and Garba[14] and Li and Smith[28] incorporated the connectivity constraint between the element-level stiffness parameters and the entries in the global stiffness matrix directly into the eigenvalue equation to get

$\frac{\partial}{\partial p}\left([\Delta A]\phi_{d_i}\right)\{\Delta p\} = E_i$, which is then solved for minimum-norm of $\{\Delta p\}$. Doebling provided a detailed derivation of the minimum rank elemental parameter update approach[32].

The majority of the early work in optimal matrix update used the minimum norm perturbation of the *global stiffness matrix*[20-22]. The correction matrices are usually constructed at the *global level* through the constrained minimization of a given weighted functional[21,22,29,30]. The motivation for using this objective function is that the desired perturbation is the one which is the "smallest" in overall magnitude. But, a common drawback of the methods is that the computed perturbations are made to stiffness matrix values at the structural DOF, rather than at the element stiffness parameter level. However, such an optimization may yield updated matrices where the symmetry and orthogonality conditions as well as the original connectivity are destroyed. Penalty techniques and Lagrangian multipliers are then often required to enforce these constraints[21,22,31], which undoubtfully increases the computational effort. Moreover, a global updating of the FEM matrices is useful only if corrections bring the understanding of what truly differs between the real structure and its modeling. With global adjustment schemes, this physical meaning is usually difficult to interpret, which makes damage prediction hazardous. In order to keep the symmetry, positive definiteness, and connectivity properties, or keep the original load pathes uncorrupted, an *element-by-element parameter based updating method* should be considered. Once the FEM has been adjusted, changes in the physical parameters of

the system are available at the element level, which greatly facilitates the understanding of modeling errors or damage locations. Computing perturbations at the elemental parameter level uses the sensitivity of the entries in the stiffness matrix to the elemental stiffness parameters so that the minimum-norm criterion can be applied directly to the vector of elemental stiffness parameters. The resulting update consists of a vector of elemental stiffness parameters that is a minimum-norm solution to the optimal update equation. There are three main advantages to computing perturbations to the elemental stiffness parameters rather than to global stiffness matrix entries: (1) The resulting updates have direct physical relevance, and thus can be more easily interpreted in terms of structural damage or errors in the FEM; (2) The connectivity of the FEM is preserved, so that the resulting updated FEM has the same load path set as the original one; and (3) A single parameter, which affects a large number of structural elements can be varied independently.

Early work in optimal matrix update using measured test data was performed by Rodden[17], who used ground vibration test data to determine the structural influence coefficients of a structure. Brock examined the problem of determining a matrix that satisfied a set of measurements as well as enforcing symmetry and positive definiteness[18]. Berman and Flannelly discussed the calculation of property matrices when the number of measured modes is not equal to the number of DOF of the FEM[19]. Several optimal matrix update algorithms are based on the problem formulation set forth by Baruch and Bar Itzhack[20]. In their work, a closed-form solution was developed for the minimal Frobenius-Norm matrix adjustment to the structural stiffness matrix incorporating measured frequencies and mode shapes. Berman and Nagy adopted a similar formulation but included approaches to improve both the mass and stiffness matrices[21]. In the previously cited work[18-21], the zero/nonzero (sparsity) pattern of the original stiffness matrix may be destroyed. Algorithms by Kabe[22], Kammer[23], and Smith and Beattie[24] have been developed which preserve the original stiffness matrix sparsity pattern, thereby preserving the original load paths of the structural model. The Kabe[22] algorithm utilizes a percentage change in stiffness value cost function and appends the sparsity pattern as an additional constraints; whereas Kammer[23] and Smith and Beattie[24] investigate alternate matrix minimization formulations. Smith and Hendricks have utilized these various matrix updates in direct studies of damage location in large truss structures[25,26]. Although minimization of the matrix norm of the difference between the original and refined stiffness matrix is justified for the model refinement case, its applicability for damage detection is open to question because damage typically results in localized changes in the property matrices; whereas the matrix norm minimization would tend to "smear" the changes throughout the entire stiffness matrix.

(3) Sensitivity Methods[33-38]: which make use of sensitivity derivatives of modal parameters such as modal frequencies and mode shapes with respect to physical structural design variables such as element mass and stiffness, section geometry, and material properties, to iteratively minimize the residual modal force vector[33-35]. The derivatives are then used to update the physical parameters. These algorithms result in updated models consistent within the original finite element program framework. The residual modal force vector is defined as $R_i = -\left(-\lambda_{d_i}\Delta M + \Delta K\right)\phi_{d_i} = \left(K_a - \lambda_{d_i}M_a\right)\phi_{d_i}$,

where the rightmost term is known and will be equal to zero for an undamaged structure. Assume that the selected measured vibrational characteristics are contained in a vector, $\Lambda^T = \{\omega^2, \phi\}^T$; Λ_a and Λ_d correspond to the analytical refined structural model and damaged structural model, respectively. The unknown structural parameters in damaged region are contained in a vector r; r_a and r_d correspond to the analytical refined structural model and damaged structural model, respectively. The relationship between these vectors can be established by using a first-order Taylor series expansion, $\Lambda_d = \Lambda_a + T(r_d - r_a) + \varepsilon$, where, ε is a vector of measurement errors associated with each measured parameter, such as natural frequencies and mode shape amplitudes. Matrix T is a *sensitivity matrix* that relates modal

parameters and the physical structural design variables, $T = \begin{bmatrix} \dfrac{\partial \omega^2}{\partial K} & \dfrac{\partial \omega^2}{\partial M} \\ \dfrac{\partial \phi}{\partial K} & \dfrac{\partial \phi}{\partial M} \end{bmatrix}_a \begin{bmatrix} \dfrac{\partial K}{\partial r} \\ \dfrac{\partial M}{\partial r} \end{bmatrix}_a$. The subscript

"a" is associated with the analytical baseline configuration, which means that the derivatives are determined from the analytical baseline data Λ_a and r_a. The four individual submatrices in the first matrix of T represent partial derivatives of the eigenvalues and mode shapes with respect to the coefficients of the stiffness and mass matrices, whereas the second matrix of T represents the partial derivatives of the stiffness and mass matrices with respect to the structural parameters r. For mode k and considering measurement points i and j, it can be shown[36],

$$\frac{\partial \omega_k^2}{\partial K_{ij}} = \frac{\phi_{ik}\phi_{jk}}{\phi_k^T M \phi_k}; \qquad \frac{\partial \phi_{rk}}{\partial K_{ij}} = \sum_{n=1}^{q} \left[\frac{\phi_{in}\phi_{jk}\phi_{rn}}{(\omega_k^2 - \omega_n^2)\phi_n^T M \phi_n} \right](1 - \delta_{nk})$$

$$\frac{\partial \omega_k^2}{\partial M_{ij}} = \frac{-\omega_k^2 \phi_{ik}\phi_{jk}}{\phi_k^T M \phi_k}; \qquad \frac{\partial \phi_{rk}}{\partial M_{ij}} = \sum_{n=1}^{q} \left[\frac{-\omega_k^2 \phi_{in}\phi_{jk}\phi_{rn}(1 - \delta_{nk})}{(\omega_k^2 - \omega_n^2)\phi_n^T M \phi_n} - \frac{\phi_{in}\phi_{jk}\phi_{rn}\delta_{nk}}{2\phi_n^T M \phi_n} \right]$$

where, n is the mode number, and q is the number of retained modes in Λ_a for assessment. The goal is to determine r_d; the components of r_d include the elements in ΔK and/or ΔM in the expression of the residual modal force vector. Direct application of nonlinear optimization to the damage detection problem has been studied by Kajela and Soeiro[37] and Soeiro[38]. In this technique, it is required that the physical design variables be chosen such that the properties of the damaged component can be varied. This presents a practical difficulty in that the number of design variables required may grow quite large, although techniques utilizing continuum approximations are discussed as one possible solution to decrease the number of design variables.

(4) Control-Based Eigenstructure Assignment Techniques[39-43]: which design a controller, known as the "*pseudo-control*", that minimizes the residual modal force vector. The controller gains are then interpreted in terms of structural parameter modifications[39]. The pseudo-control produces the measured modal properties with the initial structural model, and is then translated into matrix adjustments applied to the initial FEM[40-42]. Inman and Minas discussed two techniques for FEM refinement[40]. The first assigns both eigenvalue and eigenvector information to produce updated damping and stiffness matrices. An unconstrained numerical nonlinear optimization problem is posed to enforce symmetry of the resulting model. A second approach, in which only eigenvalue information is used, uses a state-space formulation that finds

the state matrix that has the measured eigenvalues and that is closest to the original state matrix. Zimmerman and Widengern incorporated eigenvalue and eigenvector information in the FEM using a symmetry preserving eigenstructure assignment theorem[41-42]. This algorithm replaces the unconstrained optimization approach of Ref.40 with the solution of a generalized algebraic Riccati Equation whose dimension is defined solely by the number of measured modes. It should be noted that both the sensitivity and eigenstructure assignment algorithms, which do not demand the matrix norm minimization, may prove quite suitable for damage detection.

Zimmerman and Kaouk extended the eigenstructure assignment algorithm of Ref.41 to approach the damage location problem better[43]. A subspace rotation algorithm is developed to enhance eigenvector assignability. Because load path preservation may be important in certain classes of damage detection, an iterative algorithm is presented that preserves the load path if the experimental data is consistent. His algorithm begins with a standard structural model with a feedback control, $M\ddot{w} + D\dot{w} + Kw = B_0 u$, where, M, D, and K are the $n \times n$ analytical mass, damping, and stiffness matrices, w is an $n \times 1$ vector of positions, B_0 is the $n \times m$ actuator influence matrix, u is the $m \times 1$ vector of control forces. In addition, the $r \times 1$ output vector y of sensor measurements is given by $y = C_0 w + C_1 \dot{w}$, where, C_0 and C_1 are the $r \times n$ output influence matrices. The control law taken is a general linear output feedback controller, $u = Fy$, where, F is the feedback gain matrix. Rearranging all the equations above, the structural system equation can be written as

$M\ddot{w} + (D - B_0 FC_1)\dot{w} + (K - B_0 FC_0)w = M\ddot{w} + D_a \dot{w} + K_a w = 0$. It's clear that the matrix triple products $B_0 FC_0$ and $B_0 FC_1$ result in changes in the stiffness and damping matrices respectively. These triple products can then be viewed as perturbation matrices to the stiffness and damping matrices such that the adjusted finite element model matches closely the experimentally measured modal properties. Consequently, the changes in the stiffness and damping matrices due to damage can be found. Unfortunately, these perturbation matrices are, in general, non-symmetric when calculated using standard eigenstructure assignment techniques, thus yielding adjusted stiffness and damping matrices that are also non-symmetric. Therefore, a symmetric eigenstructure assignment algorithm is used to determine the refined finite element model of the damaged structure. For the perturbations to be symmetric, the following conditions must be met $B_0 FC_i = C_i^T F B_0^T$, $i = 0, 1$. With the help of a generalized algebraic Ricatti Equation, matrices C_i can then be found, thereby the matrix triple products $B_0 FC_0$ and $B_0 FC_1$ can be computed. In general, the solution will not be unique, two conditions - keeping symmetry and the same definiteness of the original stiffness and damping matrices - will provide help to identify a best solution.

(5) Damage Index Method[44-47]: An important category of vibrational assessment techniques is to use a specially designed **damage index** to indicate the damage location and its extent. The damage index is derived based upon principles in structural dynamics. Lin suggested a type of damage index based on flexibility matrix[44]. The flexibility matrix is determined using experimental data. This matrix is then multiplied by the original stiffness matrix, with those rows and/or columns that differ significantly from a row and/or column of the identity matrix indicating which degrees of freedom have been most affected by the damage. It is then assumed that damage has occurred in structural elements connecting those degrees of freedom. Although this algorithm provides information concerning location of damage, it is difficult to determine

the extent of damage. Carrasco suggested another type of damage index based on strain energy[58]. Characterizing the damage as a scalar quantity of the undamaged stiffness matrix, an expression was obtained for element damage factors that quantify the magnitude of the damage for each mode shape. This factor may take values ranging from *-1.0* to infinity, where negative values are indicative of potential damage. The most popular damage index is based on a recently developed damage localization theory attributed to Stubbs, et al[45]. This damage localization theory has been utilized to detect and localize the damages in some of civil infrastructures, such as, a real highway bridge on the US Highway *I-40* located in Bernalillo County, New Mexico[46]. The criterion was also applied to the damage detection of an aerospace manipulating system and verified by a computer simulation[47]. Assume that a finite element model of the corresponding structure has been established. The damage index β_j for the *jth*

element is given by $\beta_j = \dfrac{1}{2}\left[\dfrac{f_{ij}^*}{f_{ij}}+1\right]$, where, $f_{ij} = \dfrac{\int_a^b \left\{\phi_i^{''}(x)\right\}^2 dx}{\int_\Omega \left\{\phi_i^{''}(x)\right\}^2 dx}$, and $f_{ij}^* = \dfrac{\int_a^b \left\{\phi_i^{''*}(x)\right\}^2 dx}{\int_\Omega \left\{\phi_i^{''*}(x)\right\}^2 dx}$, and $\phi_i(x)$

is the pre-damage mode shape, $\phi_i^*(x)$ the post-damage mode shape, *i* represents the *ith* mode. The domain Ω includes all elements in the structure concerned, the integration in numerator is implemented over the element *i*. **Damage is indicated at element *j* if $\beta_j > 1.0$.** To avoid possible false indication as a damaged element is at or near a node point of the *ith* mode, the damage

index β_j is commonly written as $\beta_j = \dfrac{1}{2}\left[\dfrac{f_{ij}^*+1}{f_{ij}+1}+1\right]$. If several modes are used in identification,

say, the first *M* modes, then, $\beta_j = \dfrac{1}{2}\left[\dfrac{\sum\limits_{i=1}^{M} f_{ij}^*+1}{\sum\limits_{i=1}^{M} f_{ij}+1}+1\right]$. The pre-damage mode shape is computed after

the finite element model is assembled. The post-damage mode shape must be extracted from the experimental measurements using certain type of system identification method. Because the vibrational characteristics needed for this criterion is mode shapes, time-domain system identification technique is more effective and accurate than those in frequency domain.

(6) System-Identification Based Method[48-52]: System identification is the name given to the class of problems where the response of a structure is used to determine the system characteristics. In other words, system identification is the process of using a limited number of measurements to identify the natural frequencies and mode shapes of the structure, and to update the analytical model of the system to duplicate the measured response. This analytical model can then be used to predict the structural response to future inputs. There are seemingly infinite number of system identification methods that have been developed. What type of system identification method should be selected depends on what type of structure is in concern, and what purpose a particular system identification method works for. For large aerospace structures, for example, damping is small, so proportional damping can be assumed in some instances, and damping can be neglected entirely in others. Also, these large structures typically have low, closely spaced frequencies which can present problems for some identification methods. Those characteristics provide the basis for narrowing the field of system identification methods. But, for most system identification methods and their applications, following common assumptions are usually included. The structural response is assumed to be linear, so that the

theory of superposition holds. The situation is considered to be stationary, so that the parameters are constants, not time varying. Also, the model of the system is considered to be deterministic, so that stochastic analysis are not necessary.

Selecting a method of system identification for damage detection can be a significant task. One approach to the problem of damage detection is the determination of areas of reduced or zero stiffness in the structure. System identification methods that focus on the stiffness properties would then be considered for this approach. The stiffness properties for a structure are represented in various ways depending on the modeling technique. Physical parameters (such as elastic modulus in a continuous model of structure) are used in some model; while non-physical parameters (such as an element of the stiffness matrix that results from a finite element model of the structure) are identified in many other methods. Therefore, the model of the structure becomes a major contributor in selecting system identification methods for damage detection.

Two methods which identify non-physical parameters for discrete model are the stiffness matrix adjustment method[22] and matrix perturbation method[48]. White and Maytum's matrix perturbation method[48] uses linear perturbation of submatrices and an energy distribution analysis as the basis to determine the changes in the elements of the global stiffness and mass matrices. The implementation of this method is considerable time consuming. The selection of submatrices requires an intuition or prior experience. Therefore, it is less suitable for damage detection. Kabe's method[22] used an initial estimate of the stiffness matrix, the known mass matrix, a limited set of measured modal data, and the connectivity of the structure to produce an adjusted stiffness matrix. Therefore, this method identifies nonphysical parameters, i.e. the elements of the stiffness matrix. Kabe used a so-called "scalar matrix multiplication operator $\otimes$", for which two matrices are multiplied, element by element, to produce a third matrix. This matrix multiplication operator provides that zero elements in the original stiffness matrix can not become non-zero elements in the final result. Each element of the adjusted stiffness matrix $[K_d]$ is the product of the corresponding elements of the original stiffness matrix $[K_a]$ and an adjustment matrix $[\gamma]$ as follows, $[K_d] = [K_a] \otimes [\gamma]$, that is, $K_{d_{ij}} = K_{a_{ij}} \gamma_{ij}$. A constrained optimization procedure is developed to minimize the percentage of each stiffness element. The error function used represents the percentage change of each stiffness matrix element, while constraints are provided from the modal analysis equations and the symmetry property of the stiffness matrix. Lagrange multipliers $[\lambda]$ are used to expand the error function to include the constraints. The resulting optimization procedure is used to solve the Lagrange multipliers. Once the Lagrange multipliers $[\lambda]$ are known, the adjusted stiffness matrix $[K_d]$ can be obtained from the original stiffness matrix $[K_a]$ and the mode shape function $[\phi]$:

$[K_d] = [K_a] - \frac{1}{4}([K_a] \otimes [K_a]) \otimes ([\lambda][\phi]^T + [\phi][\lambda]^T)$. Kabe prodides an identification method for stiffness matrix elements that does not have the problem of unrealistic couplings in result. If the adjustment in stiffness matrix was resulted from structural damage, it is clear that Kabe's method can be used to identify the damaged elements. For the situation that some elements of the original global stiffness matrix are zeros where a physical coupling does exist, Kabe's method failed to detect the damage in some of the elements. Those zeros result from that the contribution from one member cancels the contribution from another in the global assembly. When one of these members is lost function due to damage, the zero value in the original

undamaged stiffness matrix becomes a non-zero value in the damaged stiffness matrix. Kabe's method is restricted, by design, so that zero values can not be adjusted to non-zero values. Therefore, these elements of the damaged stiffness matrix can not be correctly identified[26].

Peterson et al. presented a method for detecting damage based on the comparison of mass and stiffness matrices measured prior to damage with those after the damage, rather than the comparison of respective modal parameters[49]. An advantage of this method is that the data which are compared directly indicate the presence or absence of damage. This means that no nonlinear programming problem is involved, nor is a finite element model of the structure required. The approach is based on an algorithm for transforming a state-space realization into a second order structural model with physical displacements as the generalized coordinates. The first step is to form a state-space input-output model of the structure using a model realization procedure, such as the Eigensystem Realization Algorithm (ERA)[50]. Next, the state-space model is transformed into modal coordinates, and the mass-normalized modal vectors are determined for the output measurement set using the Common Basis Structural Identification algorithm[51]. The physical mass, damping and stiffness matrices are then synthesized by determining the Schur complement of the global coordinate model[52]. By repeating the model synthesis after damage has occured, it is possible to generate new mass and stiffness matrices of the damaged structure. An element-by-element comparison of the mass and stiffness matrices of the two models directly locates and quantifies changes in the mass and stiffness due to the damage.

(7) Flexibility Method[53]: In general, structural damage can be viewed as a reduction of stiffness. Corresponding to such a reduction in stiffness, the flexibility of a damaged member is increased. In some instances, however, additional elements are not reflected by adding additional stiffness matrix since such elements will not increase, but decrease the global stiffness of the structure. That is, instead of additional stiffness, but additional flexibility is added to the structure. In order to account for the special problems arising from the addition of flexibility to a structure, non-destructive damage detection method using flexibility formulation has been considered. Topole's method[53] can be summarized as follows. The eigenvalue equation of a linear structural system is $\left(K - \lambda_i M\right)\phi_i = 0$. Using $A = K^{-1}$, which is the *flexibility matrix* of the structure, to substitute K, and pre-multiplying above equation with ϕ_i^T yields $\frac{1}{\lambda_i}\phi_i^T\phi_i = \phi_i^T A M \phi_i$.

For the damaged structure, the same equation holds, $\frac{1}{\lambda_{d_i}}\phi_{d_i}^T\phi_{d_i} = \phi_{d_i}^T A_d M_d \phi_{d_i}$, where, $A_d = A + \Delta A$, and $M_d = M + \Delta M$. Assume that there is no change in mass, i.e. structural damage is reflected only by changes of the flexibility matrix. Then, the above equation reduces to

$\frac{1}{\lambda_{d_i}}\phi_{d_i}^T\phi_{d_i} = \phi_{d_i}^T A M \phi_{d_i} + \phi_{d_i}^T \Delta A M \phi_{d_i}$. Dividing this equation by the undamaged eigenvalue equation, and rearranging the terms results in $\dfrac{\phi_{d_i}^T \Delta A M \phi_{d_i}}{\phi_i^T A M \phi_i} = \dfrac{\lambda_i}{\lambda_{d_i}}\dfrac{\phi_{d_i}^T\phi_{d_i}}{\phi_i^T\phi_i} - \dfrac{\phi_{d_i}^T A M \phi_{d_i}}{\phi_i^T A M \phi_i}$. Defining

ΔA_j as the contribution of the *jth* element to ΔA, and expressing ΔA_j in terms of a product of a scalar factor β_j representing the relative damage in element j, and the contribution of the *jth* element to the initial undamaged flexibility matrix A_j, i.e., $\Delta A_j = \beta_j A_j$, then, the above equation

can be written as $\sum_{j=1}^{n} \frac{\phi_{d_i}^T \left(\beta_j A_j \right) M \phi_{d_i}}{\phi_i^T A M \phi_i} = \frac{\lambda_i}{\lambda_{d_i}} \frac{\phi_{d_i}^T \phi_{d_i}}{\phi_i^T \phi_i} - \frac{\phi_{d_i}^T A M \phi_{d_i}}{\phi_i^T A M \phi_i}$. Designating the right-hand side as

Z_i, i.e., $Z_i = \frac{\lambda_i}{\lambda_{d_i}} \frac{\phi_{d_i}^T \phi_{d_i}}{\phi_i^T \phi_i} - \frac{\phi_{d_i}^T A M \phi_{d_i}}{\phi_i^T A M \phi_i}$, and $F_{ij} = \frac{\phi_{d_i}^T A_j M \phi_{d_i}}{\phi_i^T A M \phi_i}$ which can be viewed as an element of

the sensitivity matrix F, describing how the *ith* modal parameters are affected by changes in the flexibility of the element *j*. A new equation, $F \cdot \beta = Z$, is then produced, where F-matrix shows how the modal parameters are sensitive to changes in the element flexibilities. Structural damage, or changes in the flexibilities of the elements, could now be determined by computing the sensitivity matrix F and the residual modal force vector Z, and then solving the set of linear equations for the unknown vector β. Note that damage is generally indicated by a reduction in stiffness which means an increase in flexibility. Thus, structural damage will be denoted by positive value of β_j.

(8) Strain Distribution Method[54]: which measures changes in strain distribution from normal strain distribution patterns to assess structural damage. The concept is to detect common failure modes by strain and/or acoustic emmission measurements. Strain measurement can be used to detect most of failure modes. Strain history in metallics can also be used for prediction of the remaining structural life. This type of method has difficulty in assessing composite delamination. Delamination in a composite structure will show a measurable change in strain only when it becomes unstable in compression. Because the failure can become catastrophic at this point, strain measurement is unacceptable. Acoustic stress waves emanating from a delaminated area could potentially be distinguished from the healthy structure in a real-time environment. Strain distribution sensitivity to damage is basic to a strain-based damage detection method. This sensitivity is studied analytically using finite element models. Sensitivity studies were conducted to define the measurement density required to sense a precritical flaw.

Ott reported that normalized strain distribution was used to determine damage on a LTV A-7 wing model by comparing baseline distributions to distributions where damage was present[54]. Theoretical measurements could be taken to determine the exact flight data, and compared with strain measurements to determine the damage. The damaged structural strain distribution has two recognizable attributes. The first is the relatively rapid change in slope in the curve indicating damage. The second is that the damage curve falls outside the normal strain envelope. The second attribute, that is, the recognition of the damaged strain excursion outside the undamaged envelope, is most useful for damage detection. This approach greatly simplifies the total data requirements by eliminating exact flight data identification.

(9) Strain Energy Method[55-58]: Strain energy distribution has been used by previous researchers as an important measure in work related to structural damage detection[14, 35, 55-58]. The investigations of these work suggest that modal data contain sufficient information to identify damage only if the damaged member's contribution of its strain energy is a significant part of the strain energy of the modes being measured. A member with higher strain energy in a certain modal set stores a fair amount of energy for this particular modal set, that is, that member carries a non-negligible share of the overall loading. Thus, any modification of its material

and/or geometrical properties affects the overall dynamics of the structure. It is common therefore to assume that the identified modes which are used in the damage detection algorithm should store a large percentage of their strain energy in the members where potential damage might occur. Carrasco directly used modal strain energy for localization and quantification of damage in a space truss model[58]. The method considers the mode shapes of the structure pre- and post-damage measured via modal analysis. Values of the mode shapes at the connections are used to compute the strain energy distribution in the structural elements. Characterizing the damage as a scalar quantity of the undamaged stiffness matrix, an expression was obtained for element damage factors that quantify the magnitude of the damage for each mode shape. The total modal strain energy for the *jth* mode can be computed using the expression, $U_j = \frac{1}{2}\phi_j^T K \phi_j$, which can also be considered as the sum of the strain energy in all the structural elements,

$$U_j = \sum_{i=1}^{n} U_{ij} = \frac{1}{2}\sum_{i=1}^{n} \phi_{ij}^T K_i \phi_{ij}$$, where U_{ij} is the modal strain energy contribution of the *ith* element to the *jth* mode. Damage brings changes in element strain energy between the undamaged and damaged structures around the vicinity of the damage. These differences can be computed by

$\Delta U_{ij} = U_{ij} - U_{d_{ij}} = \frac{1}{2}\phi_{ij}^T K_i \phi_{ij} - \frac{1}{2}\phi_{d_{ij}}^T K_{d_i} \phi_{d_{ij}}$. Assuming that the nominal undamaged properties of the element be used to approximate the damaged properties of the same element, then, a damage factor α_{ij} can be defined as $\alpha_{ij} = \frac{U_{ij}}{U_{d_{ij}}} - 1 = \frac{\phi_{ij}^T K_i \phi_{ij}}{\phi_{d_{ij}}^T K_i \phi_{d_{ij}}} - 1$, which quantifies the damage for element *i* using mode *j*. This factor may take values ranging from *-1.0* to infinity, where negative values are indicative of potential damage. Practically, the computation of α_{ij} might bring some numerical difficulties. For the following cases, numerical problems may occur: (1) when damage is evaluated at an element that has little or no modal strain energy content for the corresponding mode in the undamaged and/or damaged states; (2) when the induced damage is large, the redistribution of modal strain energy may be so severe that elements with significant energy content in the undamaged state may have little or no energy content in the damaged state.

(10) Artificial Intelligence-Based Methods[59-63]: Application of the methodology in Artificial Intelligence (AI) field to structural damage evaluation has increased significantly during the last decade[59,60]. Among others, **Pattern Recognition** and **Neural Network** are two popular examples. The mathematical approaches to pattern recognition may be divided into two general categories[61], namely, the syntactic (or, linguistic) approach and the decision theoretic (or, statistical) approach. The majority application of the pattern recognition method to structural failure detection and diagnostics has been the decision theoretic approach. This is a process that is generally used to digest a vast amount of data, reduce it into a meaningful representation, and make decision on the outcome of the observation data using a classifier. Grady applied this approach to an in-flight airframe monitoring system[59]. A personal computer-based pattern recognition algorithm could be "trained" using laboratory test data, to recognize such characteristic changes in structural vibrations, and to infer from those changes the type and extent of damage in a structural component. For example, as damage develops, a loss in structural stiffness causes a corresponding decrease in the resonant frequencies of the structure, causing the frequency response curve to shift along the frequency axis. These shifts in

frequencies are related to damage characteristics during the training phase. With sufficient training input, the pattern recognition algorithm can relate typical waveform characteristics to structural damage levels. In general, four fundamental steps are required to "train" the pattern recognition algorithm: pattern measurements; feature extraction; learning; and classification. After a set of features (e.g., frequencies, damping properties) are calculated that characterize the pattern measurements (vibration signals), the classifier partitions the feature space into a number of regions, and associates each region with one of the known outcomes (e.g., damage levels). Decision making ability is established through a learning process which compiles and retrieves information based on experiences where a priori knowledge of an outcome has been established.

The basic idea of neural network application is to "train" the network with known sets of structural vibration test data, and use the network to predict or identify the structural characteristics under other operating conditions. Ganguli et al have developed a neural network model to characterize the effect of damage conditions in rororcraft structure[62]. Rosario, et al applied neural technique to the damage assessment of composite structure[63]. Although neural network has many merits, it is limited to detecting only forms of damage that have been trained into the neural network. In addition, large amounts of data and time are required to train the network to learn the system model.

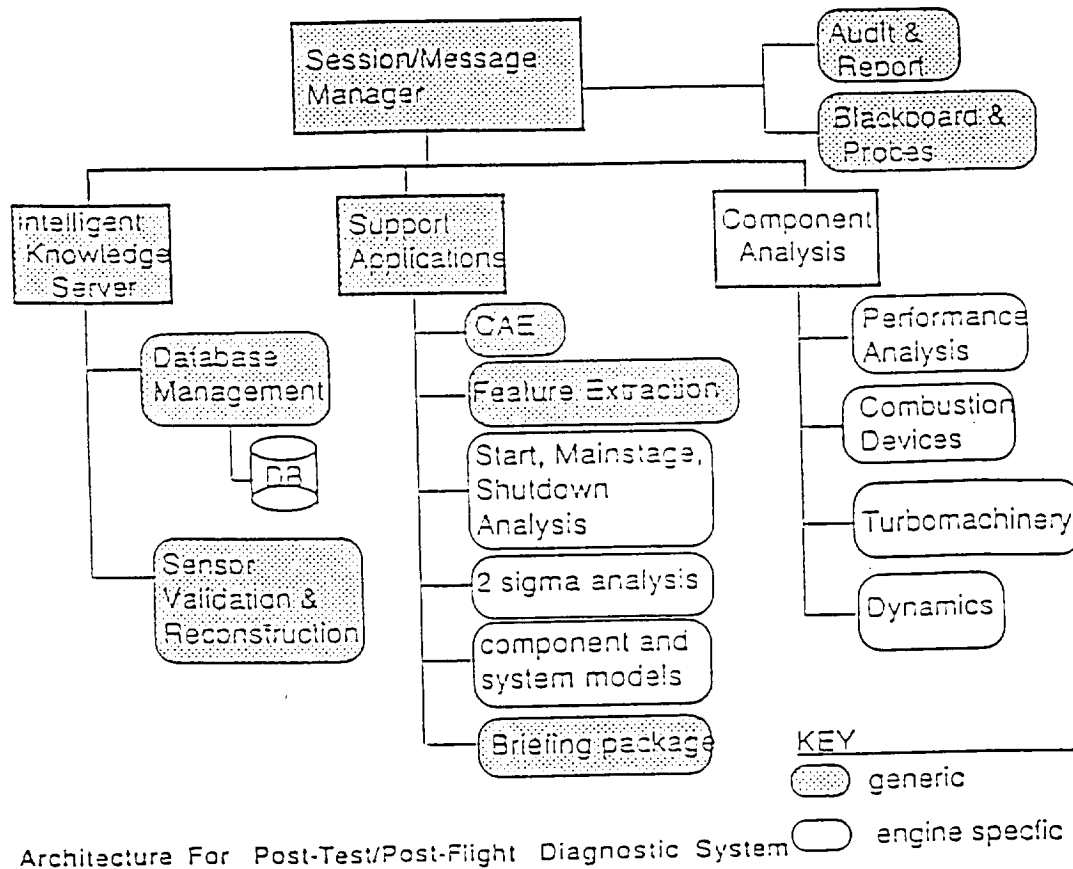# 6. Global Structure of the Suggested Structural Healthy Monitoring System

NASA's generic automated diagnostic system consists of three major sections under the Session/Message Manager: the Intelligent Knowledge Server (IKS) Section, the Support Application Section, and the Component Analysis Section, as shown in the figure of the system's architecture[1].

(1) Intelligent Knowledge Server Section: which provides a function that is basic to the data handling of the diagnostic system. It handles large amounts of data and performs the "intelligent" access to the required information sources. The tasks involved include: maintenance of local database information, providing muli-database management, providing high-level math and property queries, performing data retrieval, presenting data in a standard format, performing sensor or data validation and reconstruction, highlighting numerical points of interest, providing user or system customized tables, and providing knowledge about the previous tests with a similar anomaly.

An important module of the IKS Section is the sensor validation and reconstruction module. The purpose of this module is to review the sensor data and to verify the proper operation of the sensor at the time of measurement. If the sensor was not operating properly, then the system would provide a reconstructed value for the system to use in the engine diagnostic process. The validation is based on the comparson of the sensor data with the empirical modal data which were most successful in validating and reconstructing a sensor signal. Those data are stored in the Database Management Module.

(2) Support Application Section: which provides computer tools to the assessment of the engine. The major tools in assessing and automating the data review process are CAE tool and Feature Extraction tool. The CAE tool provides plotting, statistical analysis, and signal

processing capabilities. The Feature Extraction tool is used to extract characteristic and trend information, and produce a feature table which will help engineer to interpret the data.

Architecture For Post-Test/Post-Flight Diagnostic System
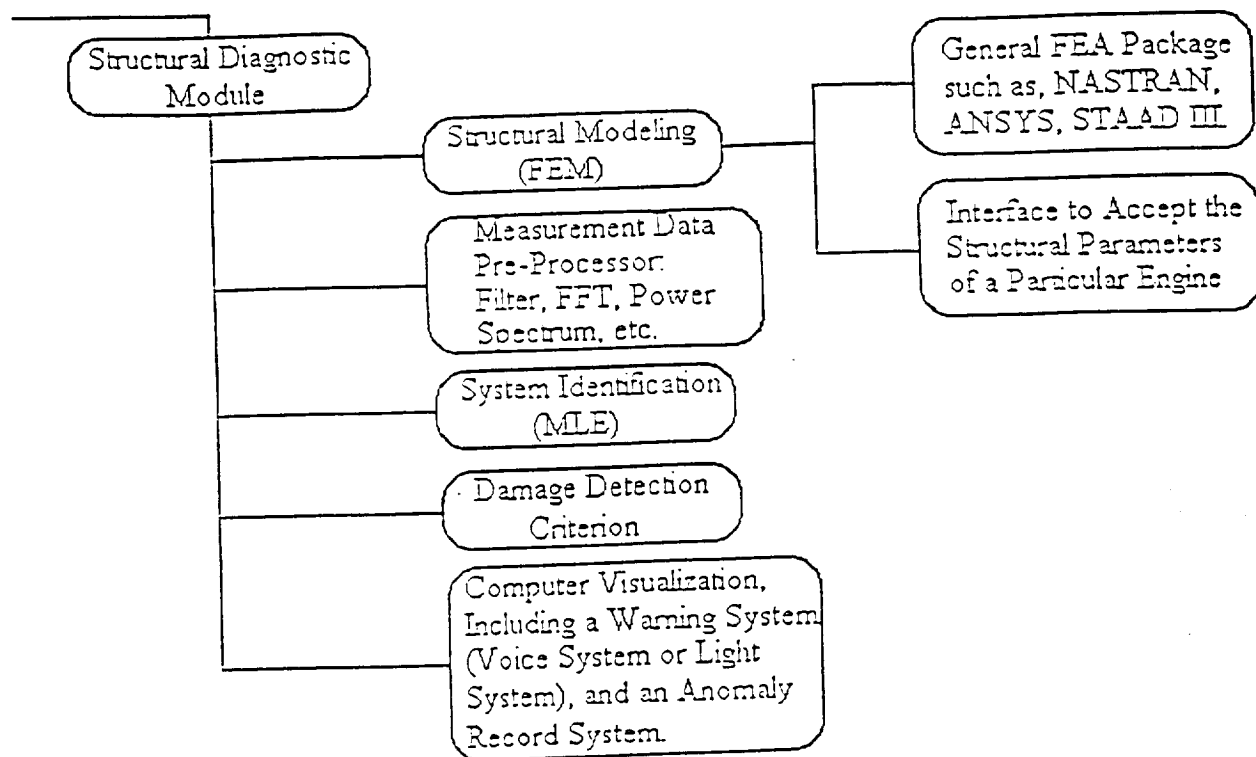
KEY
generic
engine specific

Other application modules that are included in the system are the startup analysis, mainstage analysis, shutdown analysis, two sigma exception analysis, SSME component and system models, and briefing preparation module. The startup, mainstage, shutdown, and two sigma exception analyses are application modules required by the component analysis modules. They provide core analysis routines that implement standard analysis procedures used during a particular engine phase, and provide a map of the engine during normal operation. The component and system models are existing models currently used during the data review process. The briefing preparation module is capable of preparing the text, plots and graphs necessary for the data review presentations.

(3) Component Analysis Section: which contains four major engine-specific technical modules used to analyze the SSME propulsion system. These include the performance analysis module, the combustion devices module, the turbomachinery module, and the dynamic data module. The primary function is to review the data characteristics, and assess the condition of an engine component, or entire engine system.

A new module, which functions as a non-destructive structural damage diagnosing and monitoring sub-system, is recommended to be added. This module should be consistent with the existing NASA's automated diagnostic system so that the generic core of the existing system's software can be used in common, that is, the general data review functions and software system handlers will be provided by the original system, and any customized software for a particular

engine can also be shared with the new module. Many automated features, such as, a plotting package, statistical routines, and frequently used engine and component models, provided by the existing system can also be referred. The same guidelines used in that system will be followed in the development of the structural module so that the two requirements will be satisfied for the new module. This new module consists of five sub-modules: Structural Modeling, Measurement Data Pre-Processor, Structural System Identification, Damage Detection Criterion, and Computer Visualization, as shown in the figure.

The structural modeling module will contain two sessions: a general finite element analysis package, such as, NASTRAN, ANSYS, STAAD III; etc., and an interface to accept the structural parameters of a particular engine which is thus engine-specific. The data pre-processor module will basically complete the tasks, such as, filtering, Fast Fourier Transformation (FFT), power spectrum analysis, etc. The system identification module is programmed to extract modal properties from the experimental data. Based on those modal properties, the damage detection module then localizes the damage sites. The purpose of computer visualization module is not only for providing visual impression, but also for instantly warning and anomaly recording. For some extreme cases, the incipient-type damage would progressively expand so fast that there might not be enough time to avoid a catastrophic failure, the recorded message of structural failure stored in "*black box*" would definitely have unique value for cause analysis. As an example, if we had had this type of system installed, then, we would never have had such chaos situation after TWA Flight 800 crashed into the Atlantic Ocean!

In order to complete the entire system, the research activities will include theoretical derivation, computer software development and visualization, instrumentation setup, and experimental study. The theoretical derivation covers three core parts: structural modeling, structural system identification, and damage criterion establishment. The structural model begins with conventional finite element model, and is then transferred into state-space form if it is necessary which might provide some potential features for control purpose. For example, if the concept of adaptive structure is incorporated into aerospace vehicles by using active control techniques, the damage tolerance is critical for such structures because the active control conceivably become unstable due to minor structural damage. In this case, control synthesis will be convenient if state-space equation is provided. The structural system identification algorithm is an advanced time-domain technique based on maximum likelihood estimation theory[64,65], or some other advanced techniques such as Eigensystem Realization Algorithm[50]. The damage detection criterion will be chosen from one of the advanced vibrational-based assessment techniques. The possible candidate may be the residual modal force method combined with modal sensitivity method, or damage index method. In order to develop a system for real-world engineering application, the research activities will also include computer software development and visualization, instrumentation setup, experimental measurements, and data acquisition and processing. The state-of-the-art theories and practices are systematically merged and integrated in the development of the system, and the system will be verified through the real world application of existing rocket engines.

7. Tasks for the Fiscal Year 1998 - Structural Modeling For Typical Engine Component

The task to develop the entire proposed system is very heavy. Thus, the arrangement of the tasks must have a careful consideration based upon the nature of this research project and a realistically available financial resource. The nature of the proposed work is a type of applied research, not pure theoretical research. The United States has spent a great amount of money to develop new ideas and new theoretical methods comparing with some other developed Countries such as Japan. If we can convert those theoretical research output as a practically useful devices, it will be greatly beneficial to our society. The same situation can be seen in the proposed research area. So many methods were proposed, no one method has been converted to creating a real-world applicable structural health monitoring device, although do have needs in almost all structural areas as mentioned in this proposal.

With a limited financial resource available, we suggest that the task for the Fiscal Year 1998 will concentrat on developing structural modeling techniques for typical engine components, which is the first step to start the entire research program. The following stages of the research will heavily rely on the accuracy of the model developed in this phase. A general finite element analysis package will be installed for general purpose of structural modeling. A data exchange program will be developed towards a certain engine structural components. In this stage, the finite element models of two typical types of structural components, which closely relate to the engine structures, will be developed: one is the blade on an engine rotator; and the other is the thin-walled shell-type structures such as chamber wall or nozzle wall assumed as a

hollow cylindrical thin-walled shell. Meanwhile, for the long-term arrangement, computer facility will be prepared for hosting the entire system in future. The estimated total budget for the Fiscal Year 1998 is $50,000.

8. Budget Required

Items	Cost
1. Faculty salary (Dr. Shen: $5514.78/month, three weeks)	$4,136
2. Student salary (two students, 10 hrs/week for 16 weeks, $8.50/hr.)	$2,720
3. Fringe benefit (24% of Item 1)	$998
4. Indirect cost (55% of Items1+2)	$3,771
5. Computer hardware	$24,000
6. Computer software	$7,000
7. Traveling for Conference	$1,500
8. Traveling to NASA Lewis Center (three weeks)	$3,500
9. References (Technical papers, dissertations, books, etc.)	$1,380
10. Office supplies	$1,000
Total Budget	**$50,000**

<u>**Budget Notes:**</u>

Item 1: Dr. Shen will work at LeRC for three weeks during Summer'98. The purpose is to report the progress in research and to discuss the future arrangement of the project, and for further literature searching.

Item 2: Two students will work on the project during Spring'98.

Item 5: A set of high capacity computer with large memory and high speed is planned to host the entire health monitoring system in developing.

Item 6: A general PC-based finite element package is required. Some operating system and compiling package are also required.

	Airline	Subsistence	Registration	Total
Item 7: Conference	$500	$550	$450	$1500
1 person, 1 trip, 4 days				

	Airline	Subsistence	Registration	Total
Item 8: Dr. Shen will travel to LeRC during Summer'98.				
1 faculty, 1 trip, 3 weeks	$500	$2,500	--	$3,500
(Rental car $500)				

Item 9: Buying or copying relevant reference materials.

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Appendix - About Principal Investigator